ECONOMIC GEOLOGY

AND THE

BULLETIN OF THE SOCIETY OF

ECONOMIC GEOLOGISTS

VOL. 44 SEPTEMBER–OCTOBER, 1949 No. 6

RESULTS FROM PRELIMINARY STUDIES OF VEIN FORMATION AT BUTTE, MONTANA.[1]

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ABSTRACT.

The ore-bearing veins of the Butte District are visualized as products of hydrothermal activity which was simultaneously altering the quartz monzonite host wall rock. The ratio of sulphur to sulphide-forming metals in the hydrothermal solution is postulated to exert a major determinative influence on copper-iron-sulphur series mineralogy at various zonal depths in the ore deposit. The distribution of the minerals representative of the system Cu-Fe-S as well as some of the textural relationships between them may therefore be correlated to intensity of wall rock alteration, especially to pyritization of the iron indigenous to the quartz monzonite by sulphur supplied by the hydrothermal fluid.

[1] Presented before a joint meeting of the American Institute of Mining and Metallurgical Engineers, Mining Geology Division, and the Society of Economic Geologists, San Francisco Meeting, February 1949.

INTRODUCTION.

At the New York meeting of the American Institute of Mining and Metallurgical Engineers in February 1948 the writers presented a synoptic description of the mineralogy and chemistry of wall rock alteration associated with the Butte veins.[2] It was then emphasized that, regardless of relative age, each mineralized fracture which served as a channel for the migration of ore-bearing fluid is bordered by symmetrically arranged envelopes of sericitized and argillized quartz monzonite. These two types of alteration always occupy the same relative positions: sericite adjacent to the ore-bearing vein, and kaolinite-montmorillonite mixed clay minerals between the sericitized band and fresh rock.

Because of the consistency of the foregoing pattern of distribution of alteration products and the well known structural sequence and history of the fracture complex at Butte, it was concluded: (1) that throughout the period of active circulation in ore-bearing channels there were no fundamental qualitative changes in the capacity of the ore-forming fluid to alter its channel walls; (2) that each mineralogical alteration zone migrated away from the channel by growing at its outer edge while simultaneously receding at its veinward edge because of encroachment of the next innermost zone; and (3) that vein accumulation, including sulphide deposition, was significantly integral to this orderly though complicated process by which the vein-forming solution sought to achieve equilibrium with its chemically and thermally reactive host rock.

There are interesting implications in the foregoing final conclusion to the extent that it influences interpretations regarding the processes by which the Butte ore deposits attained their currently observed character. It is our purpose in this present paper to outline the general trend of a hypothesis suggested by these implications. With continual recourse to the geological requirements of the structural history of the Butte area and to the chemico-mineralogical configuration in the host wall rocks to the veins, we propose to consider briefly some hitherto little stressed aspects of the mechanical and chemical processes of vein growth at Butte, including post-depositional history of a few of the vein sulphides.

It is well known that the planar structures now occupied by the ore-bearing veins at Butte are the loci of extreme multiplicity of fracturing, as evidenced by bifurcation and transectional gouges and crush zones and by complexity of mineral banding on both strike and dip. If one considers broadly the principal fissure patterns present over most of the district, it is clear that such major structural epochs were not sharply defined, but that there were minor readjustments following each principal regeneration of fissuring, all together producing almost a continuous process of structural adjustment of varying intensity throughout the tenure of ore deposition. A major part of each stress relief unquestionably resulted in re-faulting of rupture zones already established. But each rebreaking was also accompanied by new fractures, sometimes diverging sufficiently from the old to project outward from the already formed alteration envelopes into fresh quartz monzonite. Then hydrothermal solu-

[2] Sales, R. H., and Meyer, Charles, Wall rock alteration at Butte, Montana: T. P. 2400 Mining Technology A.I.M.E. 1948.

tions, whose intensity factor of temperature and chemical reactivity had mounted because of partial insulation from fresh rock in the old channel, would suddenly be thrust into a cooler fresh rock environment and meet conditions of drastic disequilibrium. Conversely, solutions entering a late fracture of the Blue Vein series for example, within the deep Central Zone of pervasive sericitization, would be more nearly at equilibrium with their new channel walls thermally as well as chemically.

Hence, in the face of the almost infinite numbers of combinations of circumstances conceivable in a district like Butte, the fact that a recognizably systematic district-wise pattern of mineralization and alteration has emerged is more surprising than the fact that there are frequent local divergences from that pattern. This district-wise pattern, *which is a generalization drawn by the hydrothermal process itself*, is the standard by which all of the suggested interpretations of currently observable detail set forth in this paper must be measured. It advocates the upward-migrating intensity front hypothesis already advanced by the writers for the successive envelopes of sericitization and argillization around each vein or veinlet. And, since vein formation, including sulphide deposition, accompanied alteration, there are required concurrent progressive mineral changes in the veins. The minerals nearest the source, sericite and its companions dickite and low-alkali sericite in the case of alteration products, and pyrite, chalcocite, enargite, and more rarely digenite and covellite in the case of sulphides, now observable in close association on a deep level, are believed to represent the present expression of highest intensity hypogene deposition at Butte.

After a brief summary of the process of vein growth at Butte, we shall examine some of the details of mineral occurrence and interrelationships, especially those of the copper zone with particular reference to the copper-iron-sulphur series, to see how they may conceivably be conformable to the foregoing field requirements.

VEIN GROWTH AT BUTTE.

The following analysis of the problem of vein growth rests upon the basic premises that: (1) the vein materials, other than those supplied by the walls, were brought from a deep source by solutions; and (2) the channelways were fault fissures having either simple form, or more commonly occurring in patterns of great complexity. These were supplemented by joint planes and permeability inherent in the enclosing rocks. Because of the incessant crustal adjustment and varying competence of the concurrently altering wall rocks, the typical Butte vein now appears as a complicated association of large and small interlocking individual units, with each unit displaying its own amazingly complex growth history.

Considering momentarily a small veinlet of simplest type where only one fracture plane is discernible, it is evident that attainment by the veinlet of its present width is the result of one or more of the following processes: (1) dilation of the walls through tectonic stresses of simple tension or of compression with differential movement along irregular fracture surfaces, or because of the

hydraulic pressure of the hydrothermal solution as advocated for some veins by Graton,[3] and (2) by replacement of the wall rock minerals through molecular substitution or through selective dissolution with subsequent filling of the open solution cavity or pipe by vein material.

Briefly stated, and in the broad sense just outlined, replacement of wall rocks by vein minerals appears to have been the dominant process in vein growth at Butte. According to this concept, the growth of a vein is essentially the final act of the alteration process. The effort of the hydrothermal solution to supplant fresh quartz monzonite silicates with quartz and sulphides is sometimes accomplished over a transition zone which we recognize as the silicification subzone of alteration. In other instances, however, the line of demarcation between vein and wall rock is megascopically well defined; the transition zone may not be more than one mineral grain wide. But even in the latter case, where quartz and pyrite form the marginal facies of the vein, these minerals encroach by replacement on the wall rock silicates. Frequently well-formed quartz crystals, which on their veinward sides project out into sulphides, may be observed by growth rings to have accreted to themselves more silica at their bases, so that the bases are growing away from the channel. The quartz-pyrite marginal zone is a kind of advancing mineralogical vein front, growing into the rock by consummating the final expulsion of the last silicate, sericite, and leaving only the two mineral products which are most commonly stable in the vein channel itself—quartz and pyrite. These two minerals are the common vein framework at Butte, but they are often joined in their direct encroachment on the granite by the ore mineral constituents of the veins, notably chalcocite and enargite in the Central zone, sphalerite in the Zinc zone, and rhodochrosite in the Peripheral zone.

It should be noted that according to this concept the advancing front of vein growth is an actively migrating part of the vein, and that while the pyrite and quartz of the framework are being replaced within the body of the vein by ore minerals, more pyrite and quartz are forming farther out contemporaneously with the continuing mineralization of the vein and with the advance of each alteration zone out in the wall rock. Symmetrical fulfillment of this vein growth process is limited to fractures of simple unit history—an exceedingly rare circumstance even among tiny veinlets. But degree of departure from this simple form in large veins is purely a function of repetition, at ever increasing intensity levels, of the fundamental chemical processes involved in the formation of a unit veinlet.

SULPHIDE MINERAL ZONING.

The district-wise distribution of vein minerals is a second prerequisite to a consideration of sulphide interrelationships. Though described in an earlier paper by the senior writer,[4] a brief summary of the generalized mineral zoning picture at Butte seems pertinent here.

[3] Graton, L. C., The hydrothermal depth zones: Chapter V, Ore Deposits of the Western States, A.I.M.E., p. 183, 1933.

[4] Sales, Reno H., Ore deposits at Butte, Montana: Am. Inst. Min. Eng. Trans., vol. 46, pp. 3–106, 1914.

In the Central zone and in some of the larger veins, such as the Syndicate, Colusa, and Anaconda-Original-Parrott, copper ore reached the present surface. Varying from these extremes of high tops of copper ore, which in the Central zone undoubtedly originally extended to several hundred feet above the present surface, there are those having upper limits as deep as the 3600 level. On the State vein, for example, copper ore extends up to the 1100 level in the Badger mine, while a half mile to the west in the Mt. Con it does not rise above the 3400 level, the vein being zinc-bearing from there to the surface. Similarly, on the Syndicate vein copper stopes extend to the oxidized zone in the Mt. Con mine and to the east, but westward copper ore tops at the 1200 Anselmo mine level, and the upper limit of the great orebodies of the Syndicate vein between the Mt. Con and Anselmo mines is nearly horizontal at or near the 1200 level. In both cases the copper is capped by zinc. The overall picture is that copper ore shoot apices range in elevation from the 3600 level (and probably deeper) to the surface.

An important fact to be borne in mind is that the zonal arrangement and relative proportions of enargite, chalcocite, bornite, and chalcopyrite are in part determined by geographical position in the district with respect to the Central zone, not simply by depth from the surface. For example, an ore shoot in the Badger mine, which is in Sales' Intermediate Zone, exhibits the normal succession for that locality; chalcocite, enargite, and a little bornite at lower horizons, with increasing bornite and sphalerite and scattered chalcopyrite toward the top. It is capped finally by peripheral zone mineralization containing much sphalerite with large amounts of quartz and carbonate and silicate of manganese, but with very much less pyrite than in the deeper copper zones. Generally present is a narrow transition halo of tennantite and chalcopyrite between the rich copper ore and the zinc capping. Residuals of sphalerite occur with diminishing frequency deeper in the copper zone where they nearly always appear to be replaced by the copper minerals.

On the other extreme a copper ore shoot formed wholly within the Central zone of alteration, such as the geologically late chalcocite-rich orebody of the No. 16 fault vein of the Rarus mine with its top at the 1000 level, contains almost no quartz, but only the copper minerals common to the orebodies of that zone of high intensity alteration, namely, chalcocite, enargite, and minor bornite. There is no chalcopyrite; neither is there a zinc capping above or a transition halo along the top edges. A quick narrowing to a final pinching out of rich chalcocite marks the upward failure of sulphide mineralization.

Between the extremes just mentioned there are the expected variations. Intermediate age Blue Vein copper ore shoots occurring entirely within the Central alteration zone extend much higher than those with relatively small alteration envelopes in fresh quartz monzonite only short distances away from the Central Zone.

Thus, from the district-wise viewpoint a central core of copper sulphide ores grades outward and upward through mixed copper-zinc to copper-free zinc ore in the peripheral zone. The upper limit of important copper mineralization has the generalized shape of a dome, crudely elliptical in horizontal sec-

tion and flaring outward with decreasing slope toward the depths, except in the extension of the Central alteration zone southeasterly toward the Pittsmont mine. The apex of the dome as judged by projection probably was at least some hundreds of feet above the present surface of the Butte hill, having been truncated by erosion. Structural variations as to size, type and relative age of fracturing drastically distort the upper limits of the dome and reduce the symmetry of a cross sectional view. For example, part of the Central copper zone is characterized by what has been called Horsetail fracturing now filled by closely spaced veins of small size. Proceeding westward these zones of closely spaced fracturing merge into strong, widely separated veins of great persistence along strike and dip. On this western side of the camp the iso-intensity front of zinc-copper transition is drawn out, with copper ores at deep horizons in veins that contain nothing but zinc at higher levels. By contrast, eastward from the Horsetail zone in the Leonard mine the fractures are weak. Relatively little channelization was accomplished in this direction, so the drop-off of alteration intensity and of vein mineralogy is much steeper and more abrupt.

Zonal Distribution of Copper-Iron-Sulphur Series Minerals.

Fortunately at Butte, mine workings have permitted examination of mineral associations from the surface to the deep levels in every part of the district. It has been long evident that the minerals of the copper-iron-sulphur series exhibit a preferred distribution within the copper zone which is conformable to the district-wise pattern just outlined. The remainder of this paper will be restricted to a consideration of these minerals in particular, with incidental reference only to their principal ore mineral associates, enargite and tennantite.

1. *Chalcocite and Bornite.*—As might be inferred from the preceding section steely gray chalcocite is present throughout the entire vertical range of copper mineralization, though it exhibits a definite increase in proportion to bornite at successively deeper zonal horizons. On deepest levels in the Central area of high intensity wall rock alteration its common megascopic associate is enargite. Finely divided bornite held within the chalcocite is not generally visible without the aid of a microscope. In some instances, these copper minerals are accompanied by digenite and covellite, particularly in the deep levels of the Leonard mine. Quantitatively, digenite and covellite have been only locally significant as ore minerals, but the presence of digenite in association with chalcocite, enargite and covellite is of particular genetic significance.

Butte digenite has a very distinctive appearance megascopically. It is bluish-black in color, has a well-formed conchoidal fracture and bright luster, somewhat resembling broken obsidian or anthracite coal. The finely granular appearance of steely chalcocite and the lighter gray color of the latter serve to distinguish it from digenite even at a casual glance. The composition of Butte digenite corresponds almost exactly to the formula proposed by Buerger in 1941—Cu_9S_5. The finest specimens have been taken from the stopes immediately above the 3200 level of the Leonard mine in the East Colusa orebody.

Here the writers have observed pods and lenses of digenite one to three feet wide in veins cutting highly altered quartz porphyry and quartz monzonite. Digenite, intimately associated with covellite, enargite, chalcocite and pyrite, also has been noted in quantity in the bottom of the Leonard shaft below the 3900 level, and in development crosscuts at the 3800 level where low-alkali sericite, dickite and alunite are common in vugs and in the walls immediately adjacent to the fissures.

Chalcocite, with 1 to 5 percent of included finely divided bornite, is the most abundant ore mineral of the veins within the Central zone, even where the latter extends to the surface as in the vicinity of the Mt. View mine. It also occurs in deep level portions of more outlying large veins which have thick sericitic alteration envelopes.

Proceeding zonally outward and upward from the Central zone bornite begins to make its appearance in minor quantities as small rounded megascopically sharp edged "islands" wholly within the chalcocite field. A readily distinguishable rise in the proportion of bornite takes place after the veins have emerged from the central zone of pervasive sericitization and strike through country where the intervening quartz monzonite is relatively less altered. In general, from highest intensity alteration zones outward and upward to the extreme boundaries of copper ore the bornite-chalcocite volume ratio varies between extremes of from 1 percent disseminated bornite to 50 percent or more.

It should be noted that enargite is nearly always associated with chalcocite wherever that mineral occurs, though in varying proportions. In the Rarus mine and immediately surrounding area enargite reaches its maximum development.

2. *Bornite and Chalcopyrite.*—In the extreme upper limits of a typical copper orebody whose top is below the zone of surface leaching, and where the proportion of bornite to chalcocite is high, chalcopyrite may be observed first as occasional grains at deeper levels below the ore shoot top, but increasing upwards to a sufficient proportion of the total copper present to assume commercial importance. These copper mineral ratios are widely variable depending upon geographical location in Butte's scheme of mineral zoning. In every case, however, where chalcopyrite and bornite proportions are large and that of chalcocite comparatively small, tennantite rather than enargite is the predominant mineral fixation of arsenic. But unlike enargite, tennantite never contributes more than a small proportion to the total copper content.

Geographically considered, chalcopyrite is scarce in the south half of the Butte area. It is more common though still not abundant in the northern tier of mines from the Badger westerly to the Anselmo. Only in the Syndicate vein is chalcopyrite present in sufficient proportions to account for as much as half of the copper produced from that very important orebody. There bornite is plentiful in association with the chalcopyrite, but enargite and chalcocite are scarce. It is interesting to note here that although the thickness of this chalcopyrite-bornite orebody is comparable to that of the Anaconda vein and other large chalcocite-enargite orebodies of the East-West series, the sericitic alteration envelope is very thin by comparison.

Textural Variations in the Copper-Iron-Sulphur Series Minerals.

In the score of years following presentation of the senior writer's 1913 description of field relations at Butte there appeared a number of papers by various authors commenting on the depositional sequence of Butte sulphides, especially of chalcocite and bornite. The excellent papers by Rogers,[5] Ray,[6] and Locke, Hall and Short [7] described most of the important textural relations observed between chalcocite and bornite in Butte ores.

Hence, in the present discussion we shall be more concerned with outlining the distribution of these textures than with description of them, except as it may be necessary to define clearly their spatial interrelationships. We shall conform as closely as possible to the nomenclature already established.

The following generalizations have been compiled through observation of thousands of specimens accumulated from the entire Butte district over a period of nearly 50 years. During the past several years about 5000 square inches of polished surfaces have been prepared and examined under magnifications ranging between 10 and 950 diameters. Because of the extreme susceptibility to distortion of the chalcocite lattice by heat (disorder apparently begins in some specimens at temperatures as low as 68° C), all mounted specimens were briquetted in recently developed clear, hard, cold-setting plastics.[8]

1. *Disseminated Bornite Texture.*— As we have already stated in a foregoing section of this paper, probably 95 percent of the copper derived from the zonally deepest chalcocite at Butte comes from the solid, generally fine-grained glance which resembles a freshly broken surface of mild steel. Most of the grains of this steely chalcocite have not grown larger than 1/10 mm in diameter. Throughout are dispersed tiny particles of bornite (Fig. 1). Etching

[5] Rogers, A. F., Upward secondary sulphide enrichment and chalcocite formation at Butte, Montana: ECON. GEOL., vol. 8, pp. 781–794, 1913.

[6] Ray, J. C., Paragenesis of the ore minerals in the Butte District, Montana: ECON. GEOL., vol. 9, pp. 463–481, 1914.

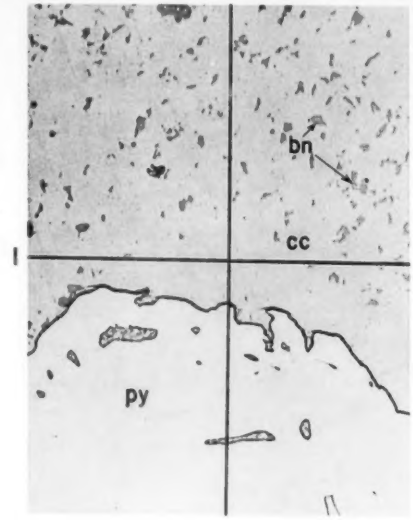
[7] Locke, Augustus, Hall, D. A., and Short, M. N., Role of secondary enrichment in genesis of the Butte chalcocite: Am. Inst. Min. Eng. Trans., vol. 70, pp. 933–963, 1924.

[8] Two cold-setting plastics have been found to be very satisfactory; *Plasticast*, sold by the Plasticast Company, Box 987, Palo Alto, California, and *Castolite*, from the Castolite Company, Woodstock, Ill. Advertisements of *Plasticast* and *Castolite* were called to the writer's attention by Warren M. Woodward and Murl H. Gidel, respectively.

Hardening of the liquid plastic is effected by the addition of promoters obtainable from the same sources. A specimen to be briquetted is simply placed face down in a water-tight mold of suitable size and the plastic poured in to fill the mold. A small piece of card bearing appropriate descriptive data may be embedded directly in the plastic before it jells.

The rate of hardening may be varied by changing the amounts of the promoters used and by slight warming (to 40° C) of the mold after gelatinization has taken place (about 10 minutes after pouring). A combination of these controls to effect completion of hardening in about one hour produces beautiful glass-clear mounts, fully cured and free from cracks and trapped bubbles.

Time-saving multiple casting of rectangular briquettes may be accomplished by the use of a small photographic tray (or similarly shaped flat vessel) as a mold. Specimens should be spaced in the tray sufficiently far apart to permit them to be cut into individual standard sized mounts on a diamond or woodworking saw after they have all been cast into one large flat block. The saw marks may be easily buffed off to restore the full transparency of the plastic, for the latter quickly assumes a brilliant polish on either cloth or lead laps. Rectangular briquettes made in this way are used at the Butte Laboratory, since mechanical polishing is done on a water-cooled lead lap adapted to a Graton-Vanderwilt polisher.



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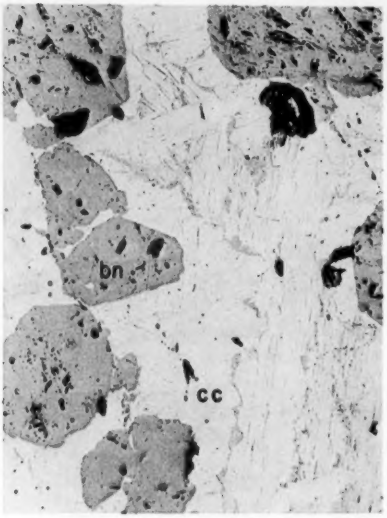

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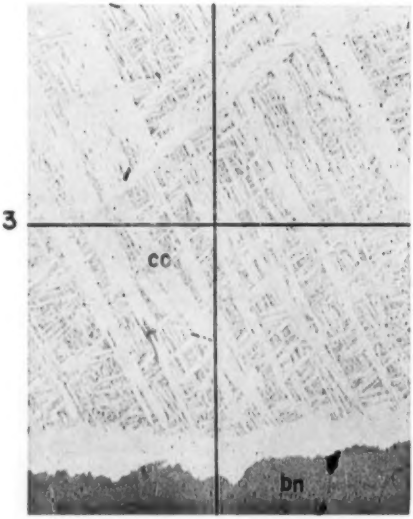

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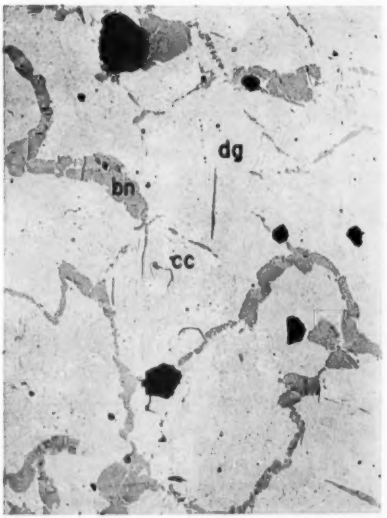

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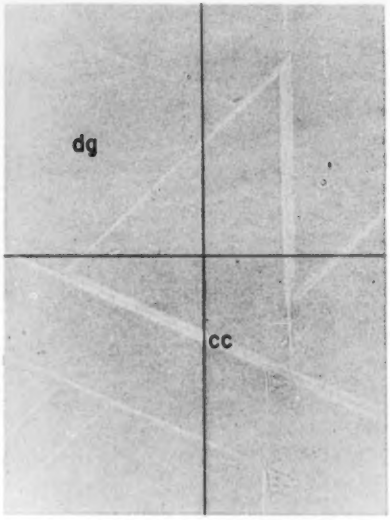
FIG. 1. Finely disseminated bornite in chalcocite, even in inclusions within pyrite grain. X 250.

FIG. 2. Disseminated bornite suboriented along crystallographic planes of coarse chalcocite; a shreddy net of bornite between chalcocite grains is also visible. Larger bornite "islands" are common in this matrix. X 17.

FIG. 3. Bornite-chalcocite grating comprising matrix to bornite "island" (lower edge). Note rim of chalcocite between grating and "island". X 200.

FIG. 4. Discontinuous bornite net in digenite-chalcocite matrix. Digenite (dg) areas contain a grating of chalcocite (Fig. 5). Most gratings have unit orientation for areas enclosed by a bornite rim, indicating that bornite net is a grain boundary pattern. Black spots are pores commonly walled by crystal faces of chalcocite and digenite in which they occur, and may have crudely hexagonal outline. X 30.



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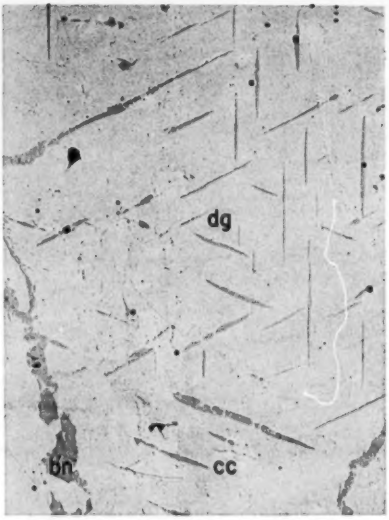

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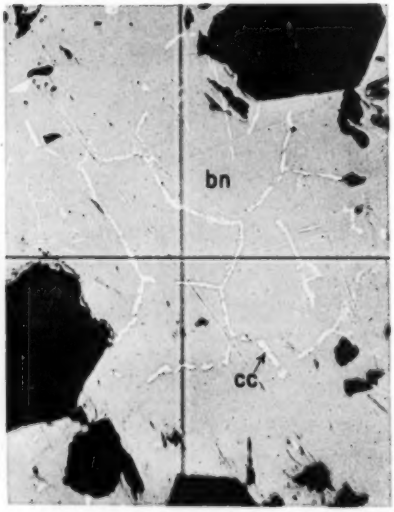

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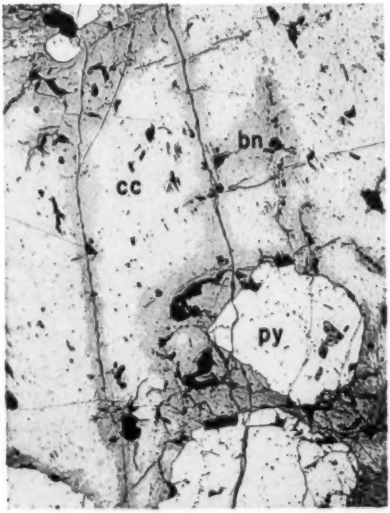

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FIG. 5. Detail of digenite area in Fig. 4, showing chalcocite grating in digenite matrix. Note that chalcocite narrows or pinches at mutual intersections. X 330.

FIG. 6. Bornite spines in digenite-chalcocite matrix with spines partly corroded or bent in the chalcocite (left side). Crudely hexagonal pores are visible (upper right). Segments of a bornite net may be seen in lower corners and comprise part of the boundary of the grid of bornite spines here shown. X 17.

FIG. 7. Grain boundary net of chalcocite in bornite. X 60.

FIG. 8. Bornite veinlets in chalcocite. Note shreddy chalcocite bordering veinlet. X 25.

reveals that these bornite granules generally occur between chalcocite grains, but so far as we have been able to determine by etching they do not have common orientation. This pattern is the most widely distributed chalcocite-bornite texture in Butte ores, for it occurs throughout the range of steely chalcocite.

What might be called a variant of the disseminated bornite pattern is found in coarser grained chalcocite (Fig. 2). Here the bornite disseminations are in general about the same size as in the texture previously described, but the chalcocite grains are much larger, sometimes attaining a length of one centimeter. The disseminated bornite in this case occurs not only between chalcocite grains but also along the internal structures of the chalcocite, in suboriented blebs along cleavage particularly.

2. *Bornite-Chalcocite Grating Texture.*—A second important pattern between bornite and chalcocite takes the form of a grating (Fig. 3) in which, as viewed in polished surface, laths of chalcocite of varying size intersect one another in a triangular grid with bornite occupying the spaces between the components of the grid. This is the interior pattern shown by most of the chalcocite having external crystal faces. It also occurs in coarsely crystalline massive chalcocite, a broken surface of which commonly shows smooth cleavage surfaces up to one centimeter or more in width along chalcocite planes, each ruled in a triangular grid of the other three directions of the octahedral pattern. The bornite component of the pattern has common orientation within the limits of one unit of the grid even though the individual bornite blebs appear to be isolated. Adjacent grid units of different orientation commonly are separated by rims of clean chalcocite or bornite.

3. *Digenite, Chalcocite, Covellite, and Bornite.*—Of considerable genetic significance to the conclusions drawn in this paper is the discovery in recent years of massive, megascopically conspicuous digenite in the deep levels of the Leonard mine, a locality displaying the highest intensity of sulphide deposition and wall rock alteration achieved at Butte. Here covellite is often closely associated with the digenite.

The space relationships of these high sulphur copper compounds and pyrite with the chalcocite-bornite members of the copper-iron-sulphur series are of interest because of the direct bearing they have toward the interpretation of all the textures in that series of minerals. There is no disseminated bornite in the digenite. Cuspate smooth bordered pods and stringers, or discontinuous nets of bornite are common but not abundant (Fig. 4). The nets are grain boundary patterns judging from observation of etch cleavage of the digenite which is the matrix mineral. Large uncorroded covellite plates are common in massive digenite which contains little or no chalcocite.

Chalcocite and digenite are often intergrown in a grating pattern (Fig. 5) which appears to be identical geometrically with the one formed between chalcocite and bornite, except that there is generally less chalcocite in digenite than in the corresponding bornite intergrowth. A distinct thinning of the chalcocite blades at their mutual intersections is an important characteristic of this pattern.

Large bornite spines [8a] are frequently present in the chalcocite-digenite grids (Fig. 6). The long axes of the spines are frequently about five to ten degrees divergent either from the direction of one lath of the grid or from bisection of the angle between two grid directions, but in other examples they show no apparent systematic geometrical relationship whatever to the grid, as noted by Locke, Hall and Short. Elsewhere the bornite spines are set in a mottled digenite-chalcocite matrix, cutting indiscriminately across the contacts between the two minerals. They are generally slightly more corroded in the chalcocite part of the field than in the digenite. On some occasions where masses of fine-grained chalcocite cut across such digenite-chalcocite grids containing bornite spines, the spines are distorted and conspicuously corroded suggesting a possible combination of mechanical distortion and mineralogical replacement. Covellite occurs in the chalcocite as minute plates arranged in a crudely triangular pattern similar to that in Kennecott, Alaska, ores described by Bateman and Lasky.[9]

A feature of prominence in the chalcocite and digenite associations of the Central zone is the conspicuously porous character of the ore. Broken or polished surfaces of the copper minerals are pocked by numerous isolate pores ranging from microscopic dimensions up to about ¼" in diameter. Typically, these are walled by crystal faces of the copper minerals in which they occur. Frequently similar openings with all the appearances of geodes are found at the centers of small clusters of pyrite crystals, which clusters are themselves embedded in currently impervious copper sulphides. Generally, these holes are lined with beautifully clean sharp pyrite crystal faces immediately adjacent to crystal faces of chalcocite and digenite in the same vug. Yet the very pyrite crystals which show the clean sharp faces in the vug are rounded and sometimes veined by the chalcocite and digenite on the other side of the crystal. According to conventional interpretations the pyrite appears to be in process of corrosion by the copper sulphides. It should also be emphasized that the cavities of both types, in pyrite clusters and in copper minerals alone, are distinctly not conjugate openings, but rather are isolated holes in otherwise solid fresh vein minerals. They reach climactic development in digenite-rich ore, where isolated pyrite-lined vugs often make up as much as 10 percent of the volume of a specimen.

4. *Bornite "Islands."*—In an earlier comment of this paper it was stated that textures of the types just described are prevalent in the Central Zone of intense sericitization at Butte. Outward from the margins of this zone a condition is approached where some of the wall rocks between individual veins never achieved fulfillment of highly intense sericitization. The argillaceous minerals kaolinite and montmorillonite, associated with more iron silicates than pyrite, are still present away from the veins, and residual boulders of nearly fresh quartz monzonite may be seen in the argillized zones. Coincident with

[8a] The word "spine" is descriptive of the bornite masses as they appear in polished surface. Considered alone and in three dimensions, the bornite component of the pattern occurs as a loose boxwork of oriented plates, each plate being thicker at and near its center and thinning toward its edges. "Spine" here corresponds to "spline" as used by Locke, Hall and Short.

[9] Bateman, A. M., and Lasky, S. G., Covellite-chalcocite solid solution and exsolution: ECON. GEOL., vol. 27, p. 60, 1932.

the lowering of intensity of alteration the smaller veins show a noticeable rise in the proportion of bornite to chalcocite, and a characteristic bornite-chalcocite texture appears. Isolated areas or "islands" of bornite, ranging in size from patches barely visible megascopically up to distinct rounded nodules about ⅜" in diameter, are dispersed in a chalcocite matrix. These bornite areas are generally more or less equidimensional, though tendencies toward variations showing distinct vermicular graphic texture are present in about a third of them. Some exhibit smoothly contoured borders. Others show ragged margins and are extensively veined by chalcocite. In numerous instances the chalcocite veinlets taper out before reaching the edges of the "island" and are cut off from the "sea" of chalcocite by a narrow sheath of bornite. Some of these truncated veinlets often have a tiny band of bornite along their center lines, while others contain disseminated bornite similar to that in the "sea" of chalcocite around the "island." The bornite "islands" may comprise from 5 to 50 percent of the volume of the chalcocite matrix in which they occur, and their even distribution throughout the chalcocite is a conspicuous feature. The writers have seen many solid unfractured lenses of such ore several feet across and tens of feet in length showing almost no discernible deviation in texture from a representative hand specimen. The chalcocite matrix always carries either the characteristic 2 or 3 percent of finely dispersed bornite which has already been described as disseminated bornite, or, in perhaps two percent of the bornite "island" ore, the bornite is intergrown with chalcocite in a grating pattern (Fig. 3). The grating texture is far less common in this type of ore than in chalcocite from deeper levels, perhaps as a corollary of the greater abundance there of chalcocite which shows crystal faces and outlines. It has not been observed in lower intensity environments than that of bornite "island" ore.

Two types of relationship between the bornite *"islands"* and the chalcocite of the grid have been studied. The spicules of grid chalcocite sometimes penetrate the very edge of the "island" to make it appear that the grid is attacking the bornite. However, the other side of the same bornite area may show a narrow rim of clean chalcocite between it and the matrix chalcocite grid (Fig. 3).

5. *Bornite-Chalcocite Graphic Intergrowths.*—The so-called graphic intergrowth, repeatedly described by various writers, is rare in deep seated chalcocite in the Central Zone but becomes quantitatively important in chalcocite ores containing bornite "islands." Most of these intergrowths require for discernment magnification under the microscope, but some attain a much larger development. Commonly, part of an "island" will be intergrown graphically with matrix chalcocite. Elsewhere tiny areas of vermicular bornite occur in the chalcocite field.

6. *Bornite-Chalcopyrite Relations.*—At zonally higher levels bornite proportion to chalcocite continues to increase, though at a more gradual rate than the relatively well defined rise where the veins emerge from zones of complete sericitization. Bornite "island" masses may become larger and more closely spaced and take on the appearance of irregular replacement by chalcocite, which itself still contains disseminated bornite. In these instances the total width of alteration measured from a 10 foot vein outward to fresh quartz monzonite

may not exceed 20 ft. At approximately this zonal level chalcopyrite makes its first appearance as equidimensional grains, which for the most part appear to be residuals undergoing replacement by bornite. The proportion of granular chalcopyrite to bornite is nearly always the reciprocal of that of chalcocite to bornite in the same specimen. Mutual patterns or those showing veining and marginal corrosion by bornite are characteristic of the massive chalcopyrite grains. Chalcopyrite tends to increase relatively to bornite around pyrite masses, where it often holds pyrite residuals in manifold variations of the appropriately named "exploded bomb" texture.

In chalcopyrite-bornite ore where chalcocite is a very minor constituent, the latter shows two textural relationships to bornite which are significant; a chalcocite net (Fig. 7) between bornite grains and a bornite-chalcocite micrographic intergrowth. In neither case does chalcocite comprise more than a very small percentage of the volume of the sample. The net consists of uniformly thin, frequently discontinuous veinlets between bornite grains. The micrographic intergrowths occur as tiny clusters of a dozen or so vermicules of chalcocite at the center of a comparatively large grain of bornite.

Chalcopyrite-tennantite associations, in multiple banding, graphic intergrowths, and mutual patterns of other types are common near the tops of copper ore shoots outside the Central Zone of alteration. This is also the copper mineralogy which characterizes the transition zone between ores of copper and zinc. There may, of course, be considerable bornite with the tennantite-chalcopyrite assemblage, but generally there is not much chalcocite.

Before concluding this section on textural description it is necessary for us to give brief mention to a significant minor texture which is common to nearly all zonal depths of copper occurrence.

Cracks in chalcocite are often bordered by bornite in the form of veinlets which apparently cut the chalcocite (Figure 8). These cracks may sometimes be traced out of the chalcocite into pyrite and quartz, establishing the fact that they are not shrinkage cracks limited to the copper minerals. The bornite veinlets may be very narrow and uniform in width or they may constitute a bornite zone as much as several inches wide bordering a plane of late fissuring in chalcocite-rich ore. The wider bornite zones are generally rather porous and crumbly in texture and may be studded with pyrite residuals.

CONTROLS ON MINERALOGY OF COPPER-IRON-SULPHUR SERIES MINERALS.

Through the careful, painstaking work of numerous investigators, notably Posnjak, Allen and Merwin in 1915,[10] Merwin and Lombard in 1924 [11] and the Buergers in 1941 [12] and later, the literature has been greatly enriched in facts concerning the mineralogy of the members of the copper-iron-sulphur series. But a few elements of uncertainty which still exist in the problem, such as the crystal chemistry and equilibria limits of some of the solid solutions

[10] Posnjak, E., Allen, E. T., and Merwin, H. E., The sulphides of copper: ECON. GEOL., vol. 10, pp. 491–535, 1915.

[11] Merwin, H. E., and Lombard, R. H., The system Cu-Fe-S: ECON. GEOL., vol. 32, pp. 203–284, 1937.

[12] Buerger, N. W., The chalcocite problem: ECON. GEOL., vol. 36, pp. 19–44, 1941.

in the Cu-Fe-S series, make us keenly aware of current interpretative limitations. What follows is therefore necessarily a preliminary and tentative statement of a hypothesis which in its general aspects we believe to be a requirement of the facts of field occurrence at Butte.

Under the circumstances of previously established simultaneous outward migration of the fronts of all mineralogical zones of hydrothermal alteration at Butte, sericitization must be construed as the product of the chemical reaction between the solution and its walls which was achieved under the highest intensity conditions attained at any point of reference during mineralization. And since the necessary ingredients and required physical environment for sericitization were supplied directly or indirectly by the hydrothermal fluid, which at the same time was depositing the vein, it is required that so long as the sericite front was advancing, the factor of intensity required for sericite was at least being maintained, probably up to the virtual conclusion of vein accumulation. Corroboration of this inference is offered by the close association and interleaving of covellite plates and other sulphides including enargite with minerals of the sericite group and dickite in vugs in the deep Leonard vein zone.

Minor fluctuations and regressions of the intensity factor, depending on local conditions controlling rate of circulation and consequently rate of supply in the channel, would not necessarily be reflected by fluctuations in position of the alteration fronts because of the relative slowness of diffusion transfer within the walls and the sluggishness of reversibility of the mineral-forming reactions there effected. But within the channel itself vein ingredients might respond by reaction or re-solution. It is the average of these fluctuations within the vein which must maintain the intensity level required for the gradual advance of mineralogical alteration fronts during the mineralization process. The zonal growth of the Butte district to its present dimensions strongly urges the proposition that at a given reference point in the vein system the intensity factor increased, on the average, during the growth of the veins. Theoretically, such a condition could easily obtain in a unidirectional process if only the rate of abstraction of heat and active chemical ingredients from the solution by the walls was less rapid than rate of decline of intensity at the magmatic gathering grounds of the solutions themselves.[13] The tendency for thermal and chemical insulation of the solution from its channel walls would permit each ascending increment of solution to lose less heat and fewer reactive ingredients than its immediate predecessor, with the consequence that the environment of intensity at any given point of reference in the channel would rise as long as supply is undiminished and circulation proceeds. At Butte the argillized zone, which itself is forming at greater distance from a vein, is replaced at its inner edge by the sericitized zone because clay minerals are no longer stable under the conditions of rising intensity which force the final breakdown of the metastable orthoclase and biotite and make white mica. And the zinc zone tends to be pushed out ahead of the copper zone because ZnS becomes unstable as a precipitated compound under the conditions of mounting intensity within the veins. The question then takes this form: Are the identity and space rela-

[13] Graton, L. C., Nature of the ore-forming fluid: Econ. Geol., vol. 35, p. 334, 1940.

tionships displayed among the copper minerals of the Cu-Fe-S series at Butte consistent with the concepts of the foregoing zoning theory?

Since white mica has been synthesized only at temperatures ranging upward from 200° C in alkaline solution and 350° C in acid solutions, and the substance of the minerals of the copper-iron-sulphur series was deposited contemporaneously with sericitization, we should consider the present mineralogical distribution in that series starting with the deposition of the necessary constituents at 200° C or higher. We must also entertain the possibility of a slow average rise in temperature and chemical potential, two important components of the composite intensity factor, until the end of effective hydrothermal supply. Following this we must consider the effects of slow decline, at possibly divergent rates, of temperature and chemical potential until the present time.

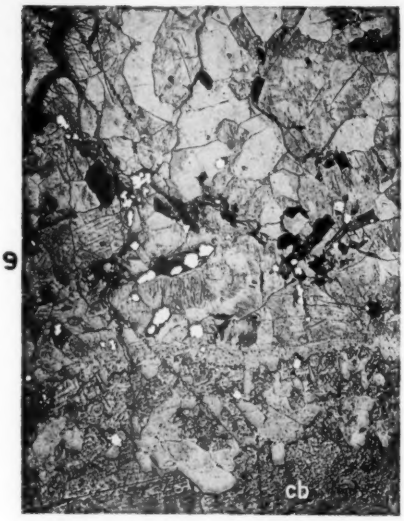
Role of Sulphur.

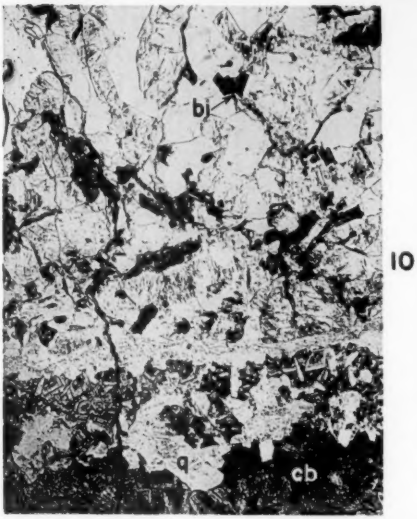
Regarding the chemical components in the composite intensity factor, an important variable concerning which we have definite information is concentration of sulphur. The importance of available sulphur in determining copper-iron-sulphur series mineralogy is currently much appreciated, especially since the work of Merwin and Lombard in 1937.

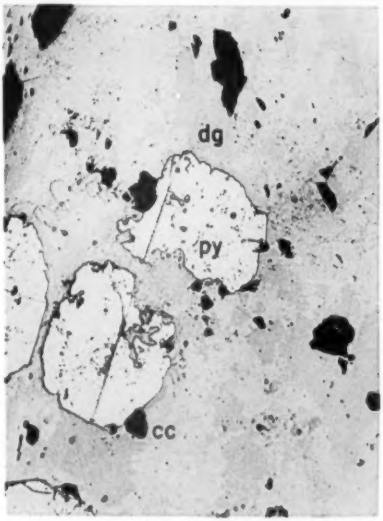
In our earlier publication on Butte alteration we pointed out that sulphur was one of the principal chemical constituents abstracted from the hydrothermal solution by the quartz monzonite walls, where it was fixed as pyrite. The precipitation of sulphides in the veins also abstracted sulphur from solution, but since most of the iron in the alteration pyrite came from the breakdown of iron-bearing rock silicates, the sulphur used in forming the alteration pyrite was taken from the solution without an equivalent loss to the solution of the metals it was transporting. The enormous tonnage of sulphur involved can be visualized by pointing out that in the Central zone of pervasive sericitization much more sulphur was fixed in the walls than was deposited as sulphides in the veins. And Butte has produced at least seventy-five millions of tons of sulphide ore from veins in the Central zone. Yet even in the peripheral zone of the camp where manganese carbonate fills many of the veins, sulphidation by the solution in the narrow zone of sericitization around those veins is still capable of precipitating all the iron released by conversion of the iron-bearing silicates to sericite (Figs. 9 and 10). But within many of these rhodochrosite veinlets pyrite is either completely absent or is present in very small quantity.

It is evident that the hydrothermal solution carried sulphur over its entire traverse of the exposed range of mineralization in the Butte district. But as long as the solution was confined to migration through channels whose walls were already completely sericitized and pyritized, that is, where all the iron in the rocks was already used up, it lost little of its sulphur over and above that required to satisfy, under the environment there prevailing, the metals which were precipitated in the veins. In other words, the ratio of concentration of sulphur ions to that of sulphide-forming metal ions in the solution [14] did

[14] For simplicity in the discussion following this ratio is designated by the name sulphur ratio.







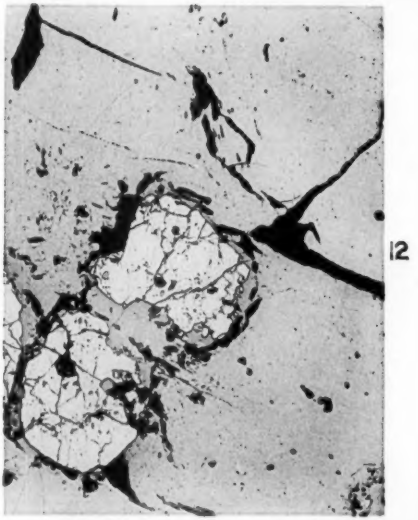
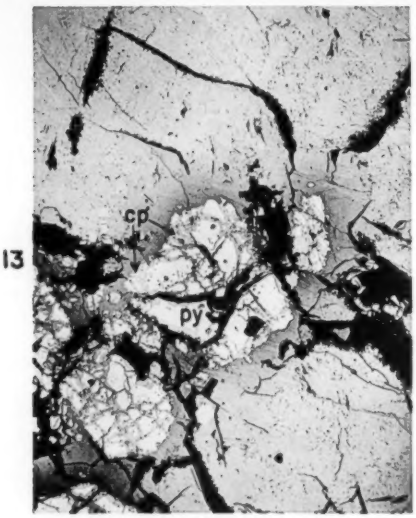


FIG. 9. Pyritization of biotite grains in sericite zone adjacent to small manganese carbonate (cb) veinlet (bottom). Note near absence of pyrite from veinlet itself and from argillized zone out beyond sericitized envelope. Polished thin section, X 8.

FIG. 10. Same field as Fig. 9 in transmitted light.

FIG. 11. Pyrite grains in field of chalcocite and digenite. X 17.

FIG. 12. Same field as Fig. 11, repolished after heating three days at 300° C in an atmosphere of H_2S. Note that chalcocite-digenite field homogenized; probably is now sulphur-rich solid solution. Pyrite remains unchanged.



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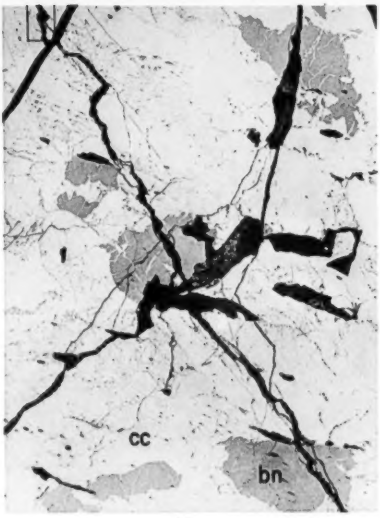

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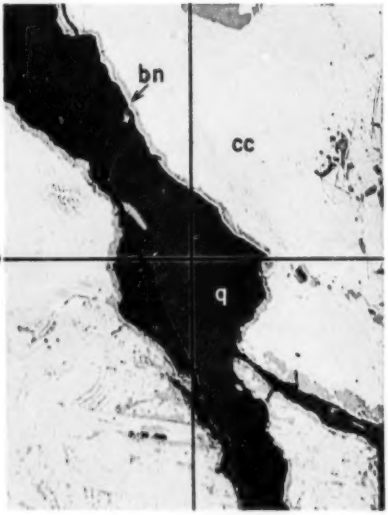

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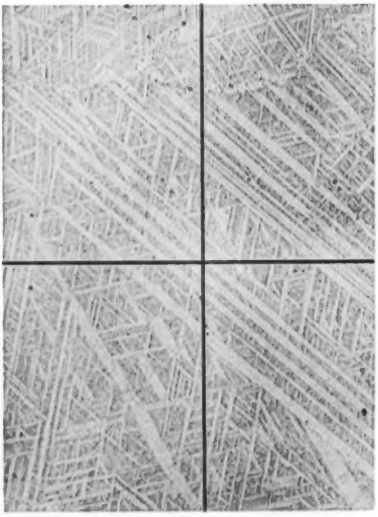

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FIG. 13. Same field as in Figs. 11 and 12, repolished after reheating for three days at 300° C in air. Note chalcopyrite (cp) reaction rim around and within pyrite grains. Dark halo around pyrite-chalcopyrite masses is iron-rich chalcocite solid solution (pink), from which bornite-like spines separated during slow cooling.

FIG. 14. Coarse chalcocite matrix containing suboriented disseminated bornite and bornite "islands". The crack running from upper left to lower right is quartz-filled. It cuts the bornite "islands" but is bordered by a rim of bornite (Fig. 15). Bornite "islands" are veined by chalcocite, but chalcocite veinlets tend to pinch before reaching the edge of "island". X 20.

FIG. 15. Field from upper left corner of Fig. 14 showing bornite rim adjacent to quartz-filled crack. X 200.

FIG. 16. Chalcocite grating in "bornite" produced by heating bornite "island" ore (Fig. 2) at 350° C for six days and then at 160° C for two months, in air at 1 atmosphere. X 200.

not greatly change so long as the solution stayed within an environment of high intensity alteration.

During its migration upward and outward from its source, however, each increment of solution would ultimately reach a point in its channel where the wall rocks were still absorbing sulphur—where the sericitized front, with its attendant complete sulphidation of wall rock iron, had not yet closed the gap between it and the sericitized zone of its closest neighboring channel. Under these circumstances a different condition prevails. Sulphur, to satisfy the iron in the walls, is removed from the solution over and above the amount necessary to combine with the metals precipitating in the channel, and the sulphur ratio in the solution must go down. Consequently, if sulphur concentration influences Cu-Fe-S mineralogy there should be a change in this mineralogy across the transition from highest intensity conditions to those of the next zone outward from the center. And since diminishing supply of excess sulphur is the rule from here on out to the rim of the mineralized area, progressive changes in copper-iron-sulphur series mineralogy should occur out to the farthest point of advance of the front of the copper zone. These observed changes already have been described. Chalcocite, containing 1 to 5 percent disseminated bornite, with pyrite and minor digenite and covellite, are characteristic of the central zone of complete sericitization, and bornite with varying amounts of chalcopyrite and proportionately less pyrite and chalcocite are the characteristic minerals of this series in outer zones of copper mineralization. Yet, averaging all the vein minerals of the copper-iron-sulphur series, the copper-iron ratio is approximately the same for all zonal levels.

Therefore, excluding other factors of the environment momentarily, high sulphur ratio in solution appears to favor stability of the simple sulphides of copper and iron, whereas relatively lower sulphur ratio favors the combined copper-iron sulphides bornite and chalcopyrite. Covellite and digenite, though quantitatively subordinate in the deepest zone, also show high fixation of sulphur. The high percentage of sulphur in pyrite, however, accounts for most of that element in Central Zone ore, for although chalcocite is low in sulphur, pyrite and chalcocite mixtures contain more of that element than mixtures of chalcopyrite and bornite having the same copper-iron ratios.

There is much experimental evidence which tends permissively to support the operation of this mechanism. Merwin and Lombard in 1937 cite an instance from their carefully controlled experiments where chalcocite and pyrite heated together at 550° C in a low pressure of sulphur, lost sulphur and yielded on cooling a yellow phase of chalcopyrite solid solution and a pinkish phase of chalcocite solid solution which looked like bornite. C. F. Park in 1931 [15] published the result of a series of experiments in which he found that chalcopyrite and bornite formed around pyrite crystals formerly encased in chalcocite. This reaction proceeded at temperatures as low as 180° C in an atmosphere of steam at ordinary pressures. Using a technique modified after Park's the present writers confirmed these results and also found that a grain of pyrite in a sea of chalcocite (Fig. 11), when heated for three days at 300° C, remained

[15] Park, C. F., Hydrothermal experiments with copper compounds: Econ. Geol., vol. 26, pp. 857–883, 1931.

stable against the chalcocite in an atmosphere of very high sulphur concentration whether the latter was provided by H_2S, Na_2S, or elemental sulphur (Fig. 12). The same specimen reacted to form the characteristic chalcopyrite-bornite reaction rims under conditions of lower sulphur concentration at the same temperature for the same length of time (Fig. 13). This reaction was also produced by the writers in Morey type bombs at calculated pressure of 1500 Kg/cm^2.[16]

Geologically at Butte this variation in sulphur ratio over the zonal length of copper deposition was a dynamic rather than a static system. We have already stressed many times that the iso-intensity fronts of alteration and vein mineralogy reached their present position by progressive migration outward and upward from the source, that is, by encroachement of each zone upon its next outermost neighbor, though we are not at present prepared to establish how far, in terms of the zonal depth of the veins at Butte, this migration proceeded. They were arrested in position only by the cessation of mineralizing activity. Thus the sulphur ratio, at any given reference point within the vein systems outside the Central Zone, was progressively increasing as circulation continued, and a curve representing change in sulphur ratio would show increase, with gradually steepening slope, of excess sulphur beginning at the lowest intensity periphery of mineralization and extending radially toward the Central Zone. The curve would show a high level of sulphur ratio within the Central Zone, but little increase closer to the source because of the relative chemical stability, in terms of sulphur at least, which obtains when Central Zone conditions are achieved.

Interpretations of Textures between Copper-Iron-Sulphur Series Minerals.

It is interesting to apply these considerations about temperature and variations in sulphur ratio, together with the concept of district-wise zonal growth and its succeeding long period of quiescence and cooling, to the interpretation of some of the textures between the members of the copper-iron-sulphur series at Butte. No attempt will be made in this short paper at exhaustive consideration of all possible "explanations" of the textures selected for discussion. Nor do the interpretations proffered herewith presume at this time to supplant others which have been advanced by other observers. They are extended merely as alternatives which apparently permissively accord in this preliminary estimate of the concept of zonal growth as applied to the Butte deposit.

As stated earlier, deep in the Central Zone the hydrothermal fluid was high in sulphur and at a temperature probably between 200° C and 400° C, depending on other qualities of the solution about which we have, as yet, no direct information. Under these combined conditions pyrite and copper sulphides were stable in contact with one another. Newly deposited copper sulphide under these conditions should have been a solid solution of Cu_2S basic composition with perhaps some extra sulphur and an amount of iron determined by the tolerance of the solid solution at the prevailing sulphur concentration. As Central Zone conditions approached achievement, hydrothermal solutions

[16] Pressure interpolated from Temperature-Specific Volume curve for water plotted by O. F. Tuttle, Geophysical Laboratory, Washington, D. C.

having higher sulphur ratios and acting on the deposited product of an earlier increment of solution, would tend to drive more of the iron out of the copper compound solid solution, thus supplying the iron, now stable as pyrite, for the bright pyrite crystal growth adjacent to copper sulphide crystals in the tiny vugs and microgeodes in the massive copper ore of this zone. Much of the porosity inherent to ores of this type may be developed during this process by reversion to compounds of lower specific volume.

Large covellite plates may be grown in the copper sulphide mass during deposition if the sulphur concentration is sufficiently high and the temperature is not above the decomposition temperature of covellite (358° C at ordinary pressure).

From Buerger's equilibrium diagram it may be inferred that under proper conditions of sulphur concentration high chalcocite and digenite might be deposited simultaneously. Or, with somewhat higher concentration of sulphur, a copper sulphide solid solution in the digenite field would unmix, on cooling, to digenite and chalcocite. The texture of Figure 6 showing bornite spines in a matrix of chalcocite-digenite grating might be interpreted to be a cooling or retrograde texture in which bornite spines, representing the maximum tolerance of iron in the solid solution at higher temperature, separated out by unmixing along the cubical pattern of digenite solid solution, and subsequently the latter solid solution itself unmixed to digenite and high chalcocite (Fig. 5). Presumably the first of these exsolutions would have developed at about 170° C, and the second, judging from the relative amounts of chalcocite and digenite in the grid interpreted in the light of Buerger's equilibrium diagram, around 150° C, under conditions of very slow cooling.

The mass of chalcocite which contains the covellite spicules transects the grating and bornite spines, apparently eradicating the digenite and heavily corroding the spines. The quantity of covellite present approximates that required to bring the chalcocite up to digenite composition, so it seems likely that we have here an instance of the partial breakdown of digenite into chalcocite and covellite. The full controls on these changes are not yet established, but the opinion might be expressed here that by facilitating removal of sulphur, or of lattice gliding, tectonic stresses applied during the long cooling process might prove effective in influencing end-product mineralogy, especially in those compounds and solid solutions which have a considerable range of metastability.

The full textural effects of cooling past the high-low inversion of chalcocite are also not yet completely known. That the recrystallizing potential of chalcocite during its inversion must be great is realized from many experiments involving annealing of that mineral. In natural occurrences of chalcocite at Butte, where cooling through the inversion range must have occupied a considerable period of time, the influence on presently exhibited textures can as yet only be surmised, but a suspicion of its efficacy in that regard may be gained from the observation that in Butte ores low chalcocite almost never shows noticeable unhealed mechanical fracturing prior to breakage by mining.

Another texture of great significance to this study is the bornite-chalcocite "island and sea" pattern found in the area immediately outside the Central

zone or above equivalent intensity conditions in an individual vein. This texture is common in the area characterized by the steepening curve of sulphur ratio that we have described earlier.

We have already pointed out that solubility of iron (or bornite) in chalcocite at a high temperature is in part a function of sulphur concentration. Under proper conditions of sulphur ratio bornite nearly free of chalcocite may be stable in contact with chalcocite solid solution low in iron. It could be deposited from fluid solution under these circumstances, or it may possibly form in the solid state by separation from chalcocite solid solution under either conditions (1) of slow cooling, or (2) of a rising sulphur ratio in successive increments of solution permeating the margins of high intensity zones during active growth of the deposit. The megascopically apparent tendency for the bornite "islands" to assume a graphic pattern and their uniform distribution through large masses of bornite-chalcocite ore support the idea of growth of the texture in place from a homogeneous solid phase.

During rising intensity conditions the bornite "islands" might thus grow so long as increasing sulphur ratio was forcing iron out of previously deposited chalcocite solid solution. With the cessation of circulation of the hydrothermal fluid, however, and the advent of post-depositional retrograde conditions of slow cooling and more rapid decline of concentration of sulphur and other chemical reactants in the stagnating solution, the bornite "islands" would be under attack by a chalcocite solid solution around them which is again capable of dissolving additional iron. The veining of the islands and their marginal corrosion may be products of this period of activity. The reassimilation of iron must have terminated abruptly, however, when during the cooling bornite-chalcocite exsolution temperature was reached. Expulsion of iron from chalcocite during the cooling period could provide the disseminated bornite and bornite-chalcocite micro-gratings which prevail in the matrix to the "islands." Continuation of the separation of bornite after the formation of bornite "islands" is suggested, for example, by the occurrence of thin rims of bornite along quartz-filled cracks which cut "island" bornite in the same microscope field (Figs. 14 and 15). The rim bornite merges with disseminated bornite in the coarsely crystalline chalcocite matrix.

In this connection mention should also be made of the micrographic textures which are so common in the chalcocite matrix. According to the mechanism outlined above, when the disseminated bornite was exsolved, bornite as a reactive separating component was *not* in excess. The bornite "island" areas were already formed and stable, under the prevailing sulphur ratio, against $c_{95}b_5$ [17] solid solution even at a high temperature. And the bornite from this matrix solid solution, when finally exsolved because of temperature decline, may form small zones of graphic intergrowth with an *excess of chalcocite only.*

Grating textures descriptively similar to those encountered in the natural Butte ores have been synthesized by Schwartz [18] and others by slow cooling

[17] Solid solution of 5 percent bornite in 95 percent chalcocite, using method of notation applied to plagioclase.

[18] Schwartz, G. M., Experiments bearing on bornite-chalcocite intergrowths: ECON. GEOL., vol. 23, pp. 381–397, 1928.

of chalcocite-bornite solid solutions. At the Butte laboratory we have grown some rather coarse gratings of this type (Fig. 16) by heating a specimen of bornite "island" ore at 350° C for six days and then undercooling at 160° C for 2 months. More irregular masses of bornite which appear to be partially replaced by chalcocite have been produced in the same way.

In many occurrences of bornite-chalcopyrite ore at Butte where chalcocite is a very minor constituent, the latter may be seen to form a tiny zone of graphic intergrowth in the center of a bornite area as we have already shown. This texture has also been synthesized in bornite specimens heated in a sulphur-rich environment. Part of the iron is driven to chalcopyrite, and slow cooling will produce the chalcocite-bornite intergrowth.

A brief consideration of the group of retrograde textures which are produced by impoverishment of the copper mineral may be mentioned in conclusion. Bornite veinlets often follow cracks cutting chalcocite at all zonal depths (Fig. 8) sometimes branching from bornite-rich zones which are common along permeable ways in otherwise solid chalcocite ore. Pyrite, apparently corroded by bornite, is common in these wider bornite zones, though the smaller veinlets obviously had iron introduced. A post-depositional reversion to low sulphur ratio, with sulphur escaping into the permeable zone, could bring about such a change of mineralogy in place, provided temperature was still high, with a minimum of transfer of materials. It should be pointed out that the *bornite* zone is the porous and permeable one, even to the point of being crumbly, while the chalcocite underneath is hard, unfractured, and comparatively far more impervious.

CONCLUSIONS.

1. The conspicuous similarity of the hydrothermal effects in and adjacent to fractures of all ages at Butte urges recognition of the essential qualitative uniformity of the hydrothermal process throughout the period of its active operation in the district.

2. This fact, considered in the light of the zonal distribution of alteration minerals and vein sulphides, requires application of a space-time concept to mineral sequence permitting all of the widely divergent alteration and vein mineral depositing processes to be active simultaneously, each at its own appropriate iso-intensity front. This concept applies to all scales of operation; to the growth of the Butte ore deposit as a whole, to unit vein formation, and even to the instance of a microscopically observed tri-mineral pattern, such as, for example, that between pyrite, chalcopyrite and bornite.

3. In the zonal growth hypothesis thus conceived, controls exerted by the changing environment at any reference point became the dominant forces influencing mineral associations and apparent mineral sequence. And the changing environment itself was a composite circumstance attained by progressive reaction between the hydrothermal solution and its thermally and chemically reactive wall rocks.

4. Important to the specific instance of copper-iron-sulphur series minerals at Butte are the potential determinative influences, on mineralogy and textural relationships, of heat and concentration of sulphur.

5. Most microtextural patterns between minerals in the Butte ores, taken individually and interpreted strictly on a basis of geometrical configuration of their components, are capable of "explanation" by several widely divergent hypotheses. In this paper we have stressed those hypotheses which appear to be consistent with the facts of broad scale field occurrence of copper ore at Butte. These hypotheses place much emphasis on exsolutions, inversions and inter-mineral reactions which took place during the time interval following the actual hydrothermal deposition of the substance of a given increment of ore. Environmental changes influencing these responses were of two types; those which occurred during progressive intensity increase because of continuing hydrothermal circulation passing the place of deposition; and those which developed during the long period of cooling after the peak of hydrothermal activity when temperature and chemical reaction potential were declining, possibly at different rates.

ANACONDA COPPER MINING CO.,
BUTTE, MONT.,
June 15, 1949.

GEOLOGICAL EXPLANATION OF GEOPHYSICAL ANOMALIES NEAR CERRO DE PASCO, PERU.[1]

F. C. KRUGER AND W. C. LACY.

ABSTRACT.

Geophysical investigation by spontaneous polarization and resistivity methods of an area containing scattered outcrops of gossan at Venencocha, on the northwest side of the Cerro de Pasco vent, delineated two anomalies so conspicuous as to suggest the presence of a sulphide body. One of these well-defined "highs" was drilled, but no sulphides were found.

Alunitization, a typical hypogene associate of Cerro de Pasco ores, correlates strikingly with the spontaneous polarization values, and the abundance of quartz remarkably parallels the resistivity readings.

It is proposed that free sulphuric acid related to the alunitization of the country rocks accounts for the spontaneous polarization potentials; and that the quartz content of the rocks is responsible for the resistivity anomalies. The possibility is entertained that a sulphide body was originally located above the present surface, but that it has now been eroded away leaving only the underlying portion of its halo of alteration.

INTRODUCTION TO PROBLEM.

It has probably been the dream of each of a long succession of geologists at Cerro de Pasco during the last thirty years that additional masses of sulphide, like the great Cerro de Pasco pyrite body, host to copper-silver and lead-zinc ores, might be located at other places around the periphery of the old volcanic vent. In this connection, several outcrops of gossan in or near limestone at a locality known as Venencocha situated along the high northwest margin of the vent had attracted attention from a time prior to the era of the present Corporation (Fig. 1). But low assays or heavy ground had invariably terminated the several campaigns of hand work from the surface before thorough testing of the area had been achieved. In 1944–5 a long cross-cut from the main workings to the east was extended to a point about 700 feet below the outcrops, and a raise carried nearly halfway to the surface, but without convincing results.

In 1946, proposal of an independent geophysical investigation was accepted by the Corporation. A spontaneous polarization survey covering this area recorded potentials of more than 700 millivolts centered some 200 feet to the east and down dip from the principal areas of gossan (Fig. 2-C). Diamond drill holes directed toward this objective yielded only barren cores and sludges, with no appreciable quantity of sulphides. A supplementary resistivity survey was made in 1947 which outlined a highly resistant area centered about 100 feet to the west of the self potential "high" (Fig. 2-D). Additional diamond drilling penetrated only barren ground.

[1] Published with permission of the Cerro de Pasco Copper Corporation.

Difficulty of identification of the altered rocks while logging the cores led to the use of the petrographic microscope, which revealed large amounts of alunite. Following this lead, more thorough petrologic studies were carried out, and form the background for this paper.

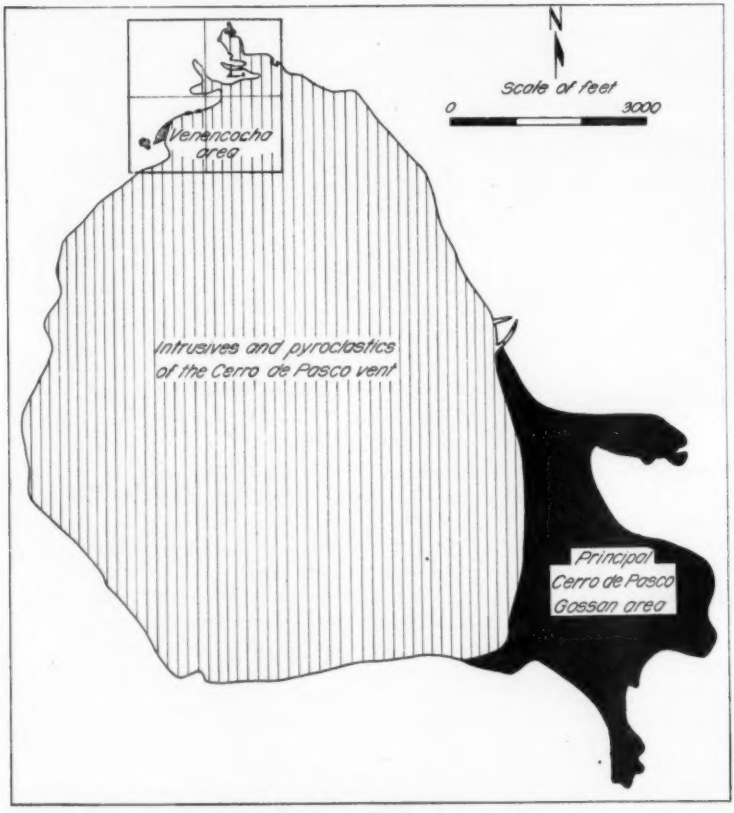


FIG. 1. Generalized map of the Cerro de Pasco vent showing the gossans and location of the Venencocha area.

GEOLOGIC SETTING.

In the Venencocha area contorted Silurian (?) Excelsior shale and quartzite are overlain unconformably by southeast dipping Carboniferous (?) Mitu quartzite and quartz-pebble conglomerate and Jurassic Paria limestone. This sequence of strata was pierced by the Tertiary quartz-monzonite intrusives and pyroclastics of the Cerro de Pasco vent (Fig. 2-A, 2-B).

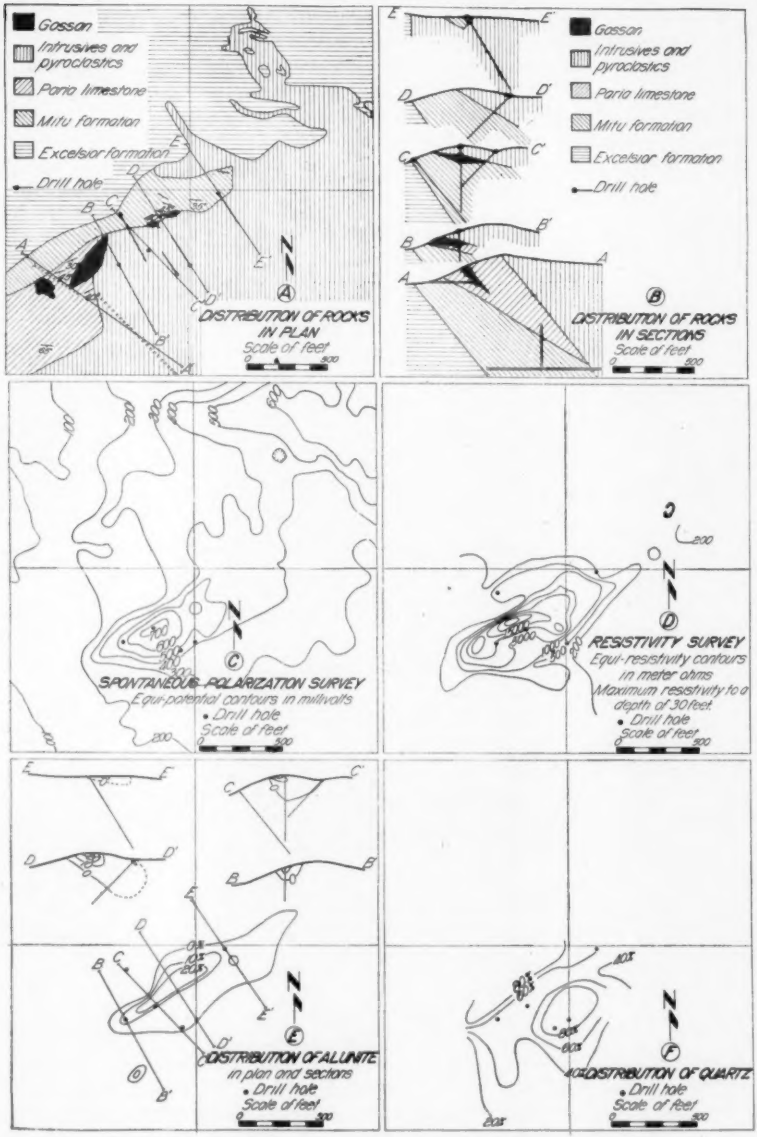


FIG. 2. Distribution of rocks and spatial correlation of geophysical results with alunite and quartz in the Venencocha area.

The eastern margin of the vent is the locus of the huge Cerro de Pasco pyritic mass, already well described in the literature. At several places on the northwestern side of the vent small areas of gossan occur. Presumably these minor gossans represent either sulphide masses oxidized in place, or precipitations from iron solutions derived by oxidation of not distant sulphides, or both. Samples from old workings give 0.2 to 4.4 percent Cu, 0.2 to 1.9 oz. Ag, and traces to 0.03 oz. Au per ton. Accumulating information indicates that the largest of these gossans dips gently to the southeast, following the bedding of the limestone as a *manto*, and pinches out laterally and in depth.

PETROLOGY.

The discovery of quantities of alunite in the drill cores from Venencocha was of particular interest because of the close zonal relationship of the alunite to much of the ore on the eastern side of the Cerro de Pasco vent (1).[2] Accordingly, 53 specimens were examined microscopically in thin section and the percentages of quartz and alunite were estimated, plotted and contoured (Figs. 2-E, 2-F). As the diamond drilling progressed 28 samples, taken at fifty-foot intervals from the cores, were studied by similar technique.

Alunite.—The Venencocha alunite occurs most abundantly in the volcanic rocks as acicular or short prismatic crystals that replace fragments of volcanic glass, fine sericitic matrix material, and oligoclase feldspars; and less abundantly as material interstitial to quartz grains and pebbles in the Mitu conglomerate (Figs. 3, 5). It is generally fresh in appearance and occurs in crystals up to 2 mm in length. The optical properties have been determined as follows: biaxial positive; $2V = 5°$; $\alpha = 1.582$; $\beta = 1.584$; $\gamma = 1.596$; negative elongation; parallel extinction; and colorless in thin section. Some of the alunite crystals have zones altering to kaolin (possibly dickite); others, where associated with later silicification, are completely kaolinized (Fig. 4).

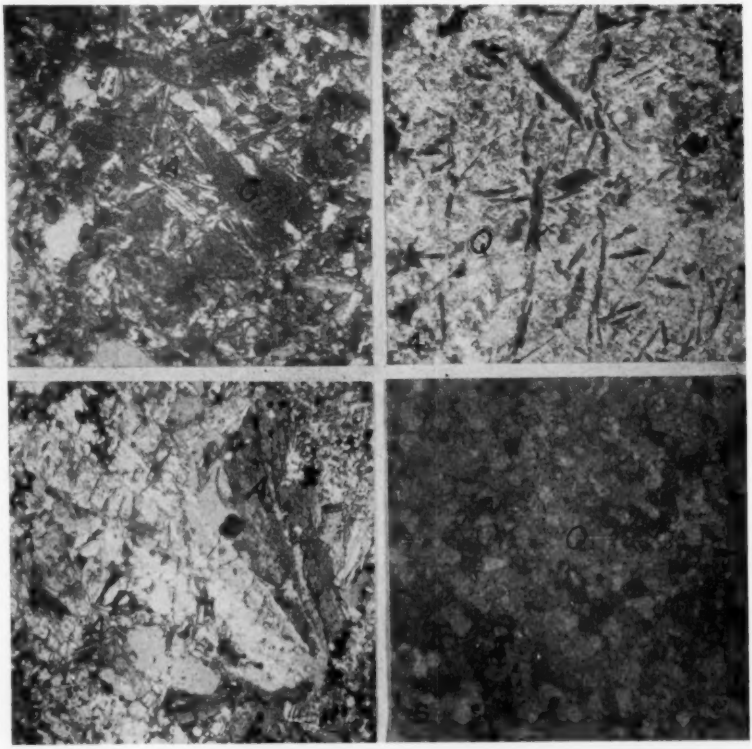
The alunite is commonly associated with secondary quartz, epidote-zoisite, and pumpelleyite, all of which are now recognized as medium to intense hydrothermal alteration minerals in the Cerro de Pasco district (1, 2). The period of alunitization appears to have been followed by silicification. Where this silicification is intense, the alunite is corroded or completely altered to a kaolin mineral of probable hypogene nature (Fig. 4). Pseudomorphs of goethite after grains of pyrite are found associated with some of the alunite, but the presence of goethite does not insure the presence of alunite, nor does the presence of alunite assure goethite.

The coarsely crystalline habit as well as the relationships with characteristically hydrothermal minerals attests to the hydrothermal origin of the Venencocha alunite.

Quartz.—In addition to the quartz present as a primary component of the rocks, quartz was introduced hydrothermally following the period of alunitization. In order to compare the distribution of free quartz with the resistivity anomalies, both the primary and introduced quartz were estimated and mapped together (Fig. 2-F). The primary quartz makes up

[2] Numbers in parentheses refer to bibliography at end of paper.

about 80 to 90 percent of the composition of the quartzitic Mitu formation, so that the effect of the later silicification is solely that of cementation. The agglomerate, tuff and accompanying quartz-monzonite of the vent in the unaltered state contain 10 to 15 percent free quartz; but this igneous material was very susceptible to reaction with the hydrothermal solutions bearing silica and has been almost completely altered to secondary quartz in the area immediately adjoining the highly alunitized area.



Photomicrographs of Venencocha rocks.

FIG. 3. Alunite (A) replacing volcanic glass (G) in agglomerate. × 38.

FIG. 4. Alunite altered to kaolin (K), corroded by fine-grained quartz (Q). × 38.

FIG. 5. Coarse alunite (A) as rosettes, replacing feldspars, quartz, and volcanic glass in agglomerate. × 38.

FIG. 6. Quartz-conglomerate (Q) with intergranular epidote-zoisite (E). × 38.

The silicification increases the hardness and compactness of the rocks affected so that they resisted erosion; and the area corresponding to the most intense silicification is topographically prominent.

Distribution of Alteration Minerals.—On the surface, the alunite occupies a rudely elliptical zone trending northeast-southwest, lying mostly in the vent rocks and paralleling the contact with the sedimentary formations. Around the outer fringes of the alunite zone, alunite is associated with epidote-zoisite, zunyite, and pumpelleyite. The entire area is silicified and is surrounded by a broad zone of silicification, which changes progressively outward into sericitized, then carbonatized, and finally unaltered rocks. In the diamond drill cores, the percentage of alunite decreases with depth, grading through a narrow silicified zone into sericitized then carbonatized or unaltered rocks. Thus it appears that the alunite zone has the form of a shallow, elongate basin or funnel lying within a zone of silicification.

Acid Content of Rocks.—These alunite-bearing rocks typically contain sulphuric acid. In order to test the quantities present, 25-gram samples of the Venencocha rocks were crushed, leached for 15 minutes with 15 cc of distilled water at 80 to 90°C, and the resulting solutions measured for pH. The readings ranged from 4.5 for an area of more than 20 percent alunite to 7.8 in the carbonatized pyroclastics. This method gave approximately 5 to 10 times the dilution that would exist in the natural occurring rock, so obviously the actual pH difference would have been materially greater than that measured. Although the pH determinations did not consistently vary inversely with the proportion of alunite in the rocks, in all instances the alunite-bearing rocks were strongly acid and the carbonatized or unaltered rocks were neutral or alkaline.

It has not been ascertained with any degree of certainty whether the sulphuric acid in the alunite-rich rocks is residual from the hydrothermal solutions that formed the alunite; released from the alunite by its conversion to kaolin; loosely held by the alunite molecule and released under lowered pressure; or some other cause.

DISCUSSION.

The similarities found on comparing the outlines of the spontaneous polarization equipotentials and the distribution of alunite (Figs. 2-C, 2-E); and also the resistivity survey and the distribution of quartz (Figs. 2-D, 2-F) are so striking that it is natural to assume a cause and effect relationship. Because only sparse sulphides were encountered by drilling beneath the area, the causative hypothesis for the alunite is especially appealing. The coincidence is given further credibility when it is considered that the strong acid content of the alunite-rich rocks coupled with the neutral to alkaline nature of the enclosing rocks would produce an ideal concentration cell.

That the regions rich in quartz should be highly resistant is self evident, but a further point should be brought out. The resistivity survey appears to have been primarily influenced by the distribution of the very siliceous Mitu formation and only secondarily by the quantity of introduced silica which

is associated with the alunite. This situation might have been predicted since the area of secondary silica carries sulphuric acid. The acid serves as an electrolyte which would tend to counteract the resistivity of the quartz.

The geological situation described above does not exclude the possibility of the existence of a sulphide mass. The presence of a sulphide body or bodies is indicated by the gossans along the edge of the vent, which appear to have formed from residual as well as precipitated iron oxides, derived from oxidation of sulphides; and by abundant alunite, secondary silica, epidote-zoisite, zunyite, and pumpelleyite, which are commonly known, in the producing area of the vent, as a halo of alteration around sulphide mineralization. Because the gossan and its enveloping zone of alteration appear to be basin or funnel-shaped and give way to unaltered rocks outward and where explored in depth, the hypothesis is proposed that the causative body of sulphides existed above the present surface and has been removed by post-Tertiary erosion and glaciation. It was fed by small feeder pipes somewhere in the bottom of the basin or funnel of alteration, or represents a downward bulge of a *manto* or more or less horizontal pipe-like structure, the feeder of which was located elsewhere along the edge of the volcanic vent. The sulphuric acid released from the alunite within this zone of alteration, lying within neutral to alkaline rocks, produced the potential recorded in the spontaneous polarization survey.

ACKNOWLEDGMENTS.

The authors wish to express their appreciation to Dr. J. H. Moses, Chief Geologist of the Cerro de Pasco Copper Corporation, and to Professor L. C. Graton of the Laboratory of Mining Geology, Harvard University, for advice and criticism in the preparation of this paper.

CERRO DE PASCO COPPER CORPORATION,
LA OROYA, PERU,
March 21, 1949.

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RESEARCH IN COAL PALEOBOTANY SINCE 1943.[1]

JAMES M. SCHOPF.

ABSTRACT.

The varied applications of paleobotany to coal resource studies, coal technology, and to fundamental physical and chemical research on coal are briefly indicated. The usual conception of paleobotany is not as broad as this, and many of the studies of fossil plants have been conducted without reference to the part the plant materials assume in composing coal. The interrelationship of paleobotany with the physical constitution and petrography of coal is an intimate one, which is too involved for treatment in the present paper. Chief emphasis is devoted to review of plant microfossil investigations during the past several years.

The consistent abundance of plant microfossils in coal and its associated rocks is now generally recognized. One of the greatest difficulties in using this material for correlation and for extending our knowledge of the plant composition of coal has been in systematic (taxonomic) treatment of the materials. The reviews of recent literature are presented chiefly with reference to the diverse systematic approaches of various authors. The contrast between essentially nonbotanical or morphologic classification schemes, which are simpler to apply and which may serve adequately for local correlational studies, and those studies conceived on a more fundamental basis of plant taxonomy, for paleogeographic and ecologic interpretation of botanically related groups, is presented. Both viewpoints should be kept clearly in mind, since differing circumstances of study and differing objectives may suggest the advisability of using one rather than the other method of systematic treatment of these fossils. No other fossils are so conveniently available from the coal deposits of primary interest.

IT is generally recognized that paleobotany has particular bearing on coal studies, but its relationships to the different kinds of coal study are not often pointed out. These relationships are varied and will be briefly summarized in introduction of the present topic.

Geologists are generally concerned with determining the extent of coal resources and on the essential characterization of coal as it exists in the coal bed. Mining engineers are interested both in these aspects and in others that affect the minability of the coal. Coal technologists are interested in the qualities of coal that occasion diversity in handling, preparation, and utilization. In all of these phases paleobotany has a direct or indirect application, occasioned by the fact that coal is primarily composed of plant-derived materials and that plant fossils associated with coal are commonly a dominant source of paleontologic data.

In the study of occurrence of coal and its metamorphism, paleobotany can assist in normal paleontologic fashion to provide information about the relative age of the deposits, their correlation, and historical interpretation. Such

[1] Published by permission of the Director, U. S. Geological Survey, and presented at the meeting of the Coal Research Committee, Society of Economic Geologists, New York, Nov. 11, 1948.

paleontologic studies are usually only incidentally related to the particular composition of coal beds and more commonly are concerned with recognition of floristic zones useful in stratigraphic correlation. Emphasis of paleobotanical studies in this connection comes chiefly as a reflection of depositional conditions that are more favorable to the occurrence of plant remains than other types of fossils.

Paleobotany also has an important application with reference to the constitutional differences observed in coal itself. Coal is derived by diagenetic and metamorphic alteration of peat. Variations in the plant composition of peat are reflected in the lithologic character, composition, and properties of coal. Plant materials are preserved in different ways in process of coalification, and these differences are initiated in the peat stage, according to the writer's conception of the problem (32).[2] Hence, the significance of any agent's action on coal depends on the effect that that agent has on diversely fossilized plant substances. These plant substances and their modes of fossilization have primary significance and probably constitute the key to inherent variations in coal to a greater extent than the chemical elements commonly reported. The latter generally appear as if they were largely indiscriminate in their occurrence throughout a coal bed, but more significance might be attached if we knew how chemical elements are associated within particular fossil plant entities. Paleobotanical interpretation is required, of course, if one is to carry out consistent sampling on this basis.

The basic problem of constitutional variation in coal often amounts to this: Granted that geologic, chemical, and various types of physical phenomena are all pertinent to the problem, what are the true effects of each of these as transmitted through a medium composed of diverse plant fossil or plant-derivative substances? For the paleobotanist the question may be transposed to read, "what is the nature of plant substances through which these various phenomena are transmitted?" An answer to such a question is of primary interest if we are to conduct a controlled fundamental investigation from the physical or chemical point of view.

Thus there are two contrasting view points about paleobotany, which, in a general way, can be thought of as complementary: (1) The paleobotanical contribution to geology that is principally related to the geology of coal resources; and (2) the paleobotanical contribution to coal petrography and the fundamental chemical and physical investigation of coal, in which the principal problem is careful definition of the modes of preservation shown by the phyto-organic aggregate.

The first viewpoint is largely that of conventional paleobotany. The second has never been formally recognized as part of paleobotany and has crept in only when some botanist was called on to assist in the petrographic interpretation of coal. In consequence, it is difficult to review the latter phase of the subject, as the items of botanical interpretation are very diffusely scattered in the literature, usually interspersed with other subjects of essentially nonbotanical nature. Furthermore, since the paleobotanists have on occasion, also

[2] Numbers in parentheses refer to Bibliography at end of paper.

made contributions to the geology, petrography, and chemistry of coal, it is not surprising that nonbotanists form diverse impressions about the scope of coal paleobotany and its essential literature.

It should also be recognized that paleobotanists are in a most favorable position to judge what environmental conditions *could* play an important part in formation of coal. Numerous theories are ruled out because they do not accord with facts of botanical observation. I suspect that such negative results are not the least of the botanical contributions to coal studies, but they are particularly unamenable to review.

There are also paleobotanical studies that have a fundamental bearing on the origin and nature of coal. These are usually conducted and reported solely because of their botanical interest. Most coal-ball studies can be placed in this category. While their value with reference to geology can be assessed in review of such literature, usually the details that have value in interpreting the particular "source" bed for the coal-balls are much less evident.

The interrelationships between paleobotany, the physical constitution of coal, and coal petrography have a long and complex history. This subject is of considerable significance and interest but is not included in the present review. A recent development to afford more consistent means of organizing the related information has been the recognition of three coordinate but different bases for distinguishing entities in coal (32). Compositional entities have been called macerals. These differ from depositional entities, termed phyterals, which are recognized by their fossil structure (2). Phyterals and macerals together stand in the same relation to coal as minerals do to sedimentary rocks. The third basis of distinction, reflected in much of the practical petrographic terminology, involves lithologic occurrence. The common petrographic terms generally involve lithologic occurrence in varying degree, in combination with other qualification of compositional or depositional nature, or both. It is this inconsistency of usage that makes coal petrography complicated and difficult for the nonspecialist to understand.

Full discussion of this somewhat involved field of borderline knowledge would not only extend the present paper beyond practical limits, but it would also infringe the topics assigned to other contributors to this program. Consequently, I have taken the liberty of restricting my present review of botanical research on coal to one branch of study that chiefly involves the philosophy of geology and paleontology, but, in contrast to much of stratigraphic paleobotany, has a special pertinence to coal. This field might be called *micropaleophytology*,[3] as it concerns the study of all kinds of plant microfossils. This subject has been long neglected, but in recent years has attracted an increased number of workers. Plant microfossil studies are progressing in many parts of the world, with a principal objective of coal-bed identification and correlation. Such studies also have considerable promise for aiding the botanical interpretation of coal, as such, but in most of the work done thus far this has not been the primary purpose.

[3] The term of broader connotation, *micropaleobotany* may be taken to refer, in general, to all the varied microscopical studies of fossil plants.

PLANT MICROFOSSIL STUDIES.

Microscopic fragments of plants are widely distributed in sedimentary rocks, and fragments showing diagnostic botanical characteristics have been found in rocks at least as ancient as those of Silurian age (19a, 19b; 13). It is possible that some forms may be present in Cambrian and even in Precambrian rocks (8, 27). Under special circumstances, plant microfossils may be of outstanding general geological service, as shown by the determination of the post-Cambrian, probably Eocene, age of the Saline series in an intensely overthrust belt in India by Sahni (28) and others. Plant microfossils thus are not limited to coal, but they probably have their greatest usefulness in relation to coal studies. Wherever they are obtained from autochthonous deposits of coal, plant microfossils reveal the general composition of plant assemblages. When coal beds are examined in detail, information can be obtained from plant microfossils about the constituent plant succession and ecologic relationships.

The composition of a fossil flora is probably more adequately represented by an assemblage of microscopic fossils than by any other available source. This is largely occasioned by the fact that all land plants possess some type of more or less waterproof membrane over the delicate surfaces of leaves and young shoots, seeds, and spores. Usually these membranes are of a waxy nature and can be recovered abundantly and in a good state of preservation from coal with more than 25 percent volatile matter.

Sometimes the floristic composition of coal beds is so diverse that the aggregate of plant microfossils affords ample evidence for distinguishing or identifying them positively without extensive study. Sometimes the floristic contrast between successive coal beds is not so great, and a more precise and detailed analysis of the succession in each bed is needed to establish reliable identifying characteristics.

The weight to be attached to plant microfossils, for the purpose of identifying coal beds, rests upon two considerations:

1. Microfossils must be determined on the basis of evidence of plant relationship and identified in groups (species) that express botanical alliance. These recognizable plant groups will not necessarily have equivalent systematic significance because invariably some kinds of microfossils show bio-characters of conservative or generalized nature; others show characteristics similar to specialized features of modern plants. The latter may be interpreted as belonging to a smaller, more narrowly defined group of plants, and therefore, can be considered to have more specific geologic and ecologic significance. Detailed botanical study must enter into the definition of microfossil groups so that their phytologic meaning can be properly interpreted and so that determinations of the microfossils identified at different localities or in different coal beds have an *essential botanical consistency.*

2. The geological problem proposed for study by means of the microfossils must have sufficient relationship to the principles of paleogeography, migration, and ecologic composition of ancient floras that statistical assemblages of microfossils have real significance. The identification of individual coal beds,

involving their differentiation from others closely spaced in the stratigraphic succession, usually poses a problem regarding a relatively short interval of geologic time. Consequently the reason for a particular frequency or absence of certain kinds of microfossils must be sought in more immediate ecological considerations than is traditional for general paleontologic studies. A factor contributing greatly to the success of the method is the relatively narrow range of environmental conditions that permit the accumulation of plant material for preservation as coal. Extraneous elements of the geologic "magnafacies" are eliminated, and a much more concise and less speculative set of conditions are presented for consideration.

CLASSIFICATION OF MICROFOSSILS.

Through use of suitable preparation techniques coal yields a wide variety of microscopic plant structures with definable botanical characteristics. No new techniques have been developed since 1943. Although some attention has been given to improvement of method, this aspect need not be discussed at the present time. Cuticular remains and several other kinds of material are frequently prominent as microfossils, but spores and pollen grains have been most studied.

A major obstacle in these investigations has been the difficulty in classifying plant microfossils, because the forms exist in abundant variety. Early in the studies it became evident that arbitrary numbering systems could be set up that might have use for purely local problems. It also became evident that the numerical systems did not begin to express the wealth of botanical information that could be made available with a more fundamental approach to such studies, and that this information would make it possible to interpret some of the less obvious similarities between different microfossil assemblages. Information about the botanical relationships of microfossils will long continue to be fragmentary. Hence any method of classification will require changes if it is to remain consistent with newer information. These principles are basic in the general philosophy of modern plant taxonomy.

Of great importance is the principle of assigning names with reference to particular specimens known as *nomenclatural types*. These type specimens serve as an objective basis for stabilizing nomenclature while at the same time the names, each associated with its particular specimen, can be treated to provide for the orderly growth of knowledge and the attendant necessary rearrangement of concepts. Thus, the nomenclature derived according to this system is more than just a series of names conventionally applied to distinctive objects—it implies a degree of botanical circumscription and a relationship to other groups of plants in the plant kingdom. The concepts of circumscription and relationship may change and *must* change as progress is made, but the specific designation is fixed by reference to the type specimen of the oldest name included in circumscription of the group. The more definite the circumscription and botanical relationship, the more useful is the concept that goes with that name. Complete systematic perfection, of course, will never be achieved, because, in a geological time perspective, botanical relationships

are always complex, and all kinds of fossil plant remains are *always* fragmentary. There can be no question, however, that some groups of plants defined on the basis of microfossils thus classified will come eventually to have wide utility and very definite botanical significance.

In 1943, L. R. Wilson, Ray Bentall, and the writer prepared a synoptic survey (33) of the apparently valid spore nomenclature then known to us that was consistent with these practices of systematic botany. In the following paragraphs, some of the work done since publication of the "Spore synopsis" and some that was not available to us then is commented on and briefly reviewed. The commentary on this literature has been arranged chiefly to present the status in regard to aspects of classification, hence it is not chronological.

REVIEW OF RECENT "SPORE" LITERATURE.

One of the outstanding omissions from the "Spore synopsis" was material from the Russian literature. Abstracts of the Seventeenth Geological Congress indicated (33, p. 10) that spores had been used effectively in correlation of coal beds and in more general determinations of geologic age. Some of this literature has become available in the reports of the Seventeenth Congress (24, 20), the English translation of which arrived in this country in 1947, and in a descriptive atlas by Luber and Waltz (20). Naumova (24) refers to an atlas of spore forms, compilation of which was first suggested by Zalessky, but this is still not known to the writer. Presumably the Naumova (14) manuscript, "Spores of the Moscow Basin," referred to by Elovskaya in 1936, is the same, or part of the same, compilation. If so, it seems evident that some later changes were made in Naumova's scheme of classification because the "Apterales" and "Pterales," which Elovskaya credits to Naumova, do not appear in the synopsis of the latter's classification given in the Seventeenth Congress report.

Elovskaya (14) described and illustrated seven spore types from the Barzas coal of the Kuznetsk Basin. No taxonomic system was followed in classifying them. The Elovskaya types 1 and 2 probably represent different species of *Punctati-sporites*. Type 3 probably includes at least two species of rather generalized character; the small (*ca.* 100 mu diam.) thick walled (*ca.* 2½ mu), smooth form may also be referable to *Punctati-sporites* but the large form (276 mu diam., wall *ca.* 6½ mu thick), probably would be assigned elsewhere. Elovskaya type 4 (av. diam. *ca.* 140 mu) appears referable to *Calamospora*. There is some doubt whether types 5, 6, and 7 (narrow, broad, and thin, *i.e.*, membranous, "winged" forms) are specifically different. They may represent *Cirratriradites*, or, possibly, *Endosporites*. In general outline they resemble *Cirratriradites gracilis* (Zerndt) S. W. and B.,[4] being only somewhat smaller (body *ca.* 130–160 mu diam., total diameter *ca.* 230–300 mu) than that species.

Luber and Waltz (20) described in 1938 over a hundred Paleozoic species represented by microfossils. Among them are 20 species previously described

[4] This form of abbreviation can be used conveniently and in accordance with general systematic practice in reference to Schopf, Wilson, and Bentall, who created many new nomenclatural combinations in the "Spore Synopsis" (33).

and named by Ibrahim (1933) and three described by Loose (1934). The system of classification is essentially that of Naumova, discussed below. The species all are illustrated by reasonably good drawings or by photomicrographs, several by both. A great number of the forms appear to be similar to those in other Carboniferous coals in Europe and America.

Among the papers included in reports of the Seventeenth Geological Congress, which appeared in Russian in 1939, is that of Naumova (24) which describes in some detail the classification of spores and pollen from coals of the USSR. Naumova bases her classification (1) on mode of germination (Trilete, Monolete, Alete, for pteridophytic(?) spores; with germinal pores or not, among spermatophytic(?) pollen), and (2) on the ornamentation, sculpture, and similar characteristics. Naumova regards the first basis of classification a "natural" one; the second is admittedly purely morphologic. However, none of the features utilized are coextensive within the large groups of fossil or modern plants and there seems to be very little correspondence with the natural system of classification as it is commonly understood. The spermatophytic and pteridophytic spores (including pollen) cannot be strictly separated by consideration of any single morphologic features, and the nearest approach to a natural classification must derive from consideration of all characters that have systematic implication. In certain groups (*e.g.*, the Schizaeaceae) the ornamentation is a better guide to affinity than the trilete or monolete mode of dehiscence (34).

In Naumova's classification the group "Rimales" includes the large groups *Triletes* and *Monoletes*. It is important to note that the Russians follow Reinsch's original usage of *Triletes* (25, 26) and apply the name to *all* trilete spores rather than to the restricted generic group of lycopsid alliance indicated by usage of Kidston, Bartlett, Zerndt, or of the present writer, who formally proposed emending the definition in a generic sense (29). If Rimales are taken as an ordinal subdivision of the classification, *Triletes* in this sense would perhaps correspond with a "suborder" or a "family," but the natural alliance is enormously and indefinitely larger than this would suggest. This *Triletes* (s. a.!) group is subdivided into two main subgroups (= family or tribe(?)), the *Azonotriletes* and the *Zonotriletes*. Designations corresponding to generic names under *Azonotriletes* are: *Leiotriletes* (smooth), *Trachytriletes* (shagreen), *Acanthotriletes* (spiny), *Lophotriletes* (tuberculate), *Dictyotriletes* (reticulate), *Brochotriletes* (alveolar), *Camptotriletes* (flexuous dissected), *Periplectotriletes* (with interwoven plications), and *Chromotriletes* (having concentric projections). Under *Zonotriletes* (tribe(?)) are nine additional subgroups (genera) distinguished by the outline of equatorial appendages (flanges and/or bladders).

Under Rimales, Monoletes, are only two subgroups: *Azonomonoletes* and *Zonomoletes*.

Under spermatophyte pollen Naumova lists Class A, Aporosa, with seven groups (families ? or tribes ?) included: the Infriata, Saccata, Intorta, Trilobata, Marginata, Plicata, and Euaporosa. Under Plicata, for example, four subgroups, corresponding to genera, are listed as follows: *Monoptycha* (with

one fold), *Diptycha* (with two folds), *Triptycha* (with three folds), and *Polyptycha* (with more than three folds). Under Trilobata we have *Brachytrilistrium* and *Dolichotrilistrium.*

Under Class B, Porosa, six groups are listed, of which *Tetraporosa* (four pores) is an example, including the "generic" subgroups *Tetraporina* (without folds) and *Ptychotetraporina* (with folds).

It seems clear to the reviewer that a great deal of empty nomenclature is entailed by this system of classification. The vagaries of compression in preservation would apparently influence how many folds were present and, hence, determine which of the "generic" subgroups would be utilized for naming material. I have the impression that these group and subgroup names can have no useful taxonomic application in the sense they have been employed by Naumova. However, if the subgroup names can be typified generically, as the genera proposed by Ibrahim have been (33 p. 30), they may be available for valid use providing they have priority. Such questions still cannot easily be decided because not all of the basic Russian literature on the subject is available.

Naumova lists species characteristic of the Devonian, Lower Carboniferous (European province, Karaganda province), Middle and Upper Carboniferous (of Donetz and the Ruhr), Permian (Donetz province and Siberian province), Upper Triassic (Uralian province), Jurassic and Lower Cretaceous (East Asiatic province), and the Upper Cretaceous and Tertiary. The differentiation of the floristic provinces is of considerable interest and when fully reported will probably hold much significance. Angiosperm pollen is said to appear first in Jurassic coals of the Caucasus; in the far east it does not appear earlier than the Upper Cretaceous. No illustrations of this interesting material are given, nor is the fossil specifically identified.

In a contribution following that of Naumova in the reports of the Seventeenth Congress, Luber (21) does not discuss details of microfossil classification. He simply uses a numerical system to designate types, and discusses their application to more specific problems of coal-bed identification and zonal correlation. He suggests that bed correlations are possible by use of assemblages from drill cores spaced as far apart as 18 kilometers. A more general correlation of certain groups of beds was established, by use of spores, between the Sary-adyr coal basin and that of the Karaganda located about 250 kilometers farther south. Spores have been very useful in tracing the synonymy of particular beds in the New Kizel coal basin where distances no greater than 6 kilometers were involved.

In Scotland Mrs. Knox (17, 18) has contributed papers continuing the work initiated nearly 20 years ago by Raistrick in England. The paper presented in 1945 on the spore distribution in central Scotland contains spore frequency diagrams for 17 coal beds, taken from some 22 localities in all. Except for one suite of samples, the area included is all within a radius of 5 or 6 miles. The spore content of some of the beds is said to be remarkably uniform from place to place, whereas in others it is variable. Some of the rare accessory spores and the "E" type spores appear to have restricted stratigraphic ranges. The basic data are presented only by means of small-

1. Rel. A1 = *Denso-sporites* sp.
2. Rel. A3 = *Denso-sporites* sp.
3. Rel. A5 = *Denso-sporites* sp.
4. Rel. B1 = *Laevigato-sporites* sp.
5. Rel. B5 = *Calamospora* sp.
6. Rel. B6 = *Incertae sedis*
7. Rel. B6 = *Punctati-sporites* sp.
8. Rel. C1 = *Endosporites* sp.
9. Rel. C3 = *Reticulati-sporites* sp.
10. Rel. D1 = *Lycospora* sp.
11. Rel. D3 = *Punctati-sporites* sp.
12. Rel. D4 = *Granulati-sporites* sp.
13. Rel. D6 = *Granulati-sporites* sp.
14. Rel. E3 = *Raistrickia* sp.
15. Rel. E4 = *? Raistrickia* sp.
16. Rel. E6 = *Punctati-sporites* sp.
17. Rel. F1 = *? Reticulati-sporites* sp.
18. Rel. F5 = *?? Reticulati-sporites* sp.
19. Rel. G = *Incertae sedis* ??
20. Mil. 5 = *Florinites* sp.
21. Mil. 6 = *Laevigato-sporites* sp.
22. Mil. 9 = *Reticulati-sporites* sp.
23. Mil. 9 = *Cirratriradites* sp.
24. Mil. 10 = *Triquitrites* sp.

FIG. 1.

scale frequency diagrams, no direct percentages being given, so it is difficult to evaluate this work.

The more recent paper by Mrs. Knox (18) reports types of small spores from coals of the Limestone Coal group. The spore types are more varied and numerous than those obtained from coals of the Productive Coal measures. Mrs. Knox recognizes 65 types from the Productive Coal measures, and 90 from the Limestone Coal group; 27 types are common to both. The most important contribution is the publication of pencil drawings of over 40 different spore types, including those designated 2K, 4K, and 9K, continuing in numerical sequence to 47K; also Raistrick's D7 and D11 and a few additional specimens that are compared with spores of modern mosses. Stratigraphic ranges are suggested, but no frequencies are reported. A number of forms appear to be irregular in distribution and are regarded as of little value for

the purpose of specific bed correlations. However, the assemblages from the Limestone Coal group as a whole differ significantly from those of the Productive measures.

Similar studies of spore assemblages have been conducted by Dr. J. O'N. Millott (*22*) in North Staffordshire. In 1945 this author presented a paper describing evidence from spore studies which corroborates the correlation by Wolverton Cope of coal beds in Cheadle with those of the Potteries coal field as based on other evidence. The productive measures of the two coal fields are separated by a gap of only about half a mile at the closest point across the Wetley Rocks anticline, but there is sufficient difference in depositional conditions, interval, and complexities owing to structure and faulting that a decisive correlation had not hitherto been achieved. All told, a detailed correlation extending over a distance of 15 to 20 miles, apparently is accomplished.

Millott has presented spore data in tabular form, giving comparative frequencies, so it is possible to compare this information independently in graphic fashion. The accompanying chart (Fig. 1) has been prepared for this purpose. Cope's geologic correlation, which does not differ from Millott's conclusions, has been used as a stratigraphic base. Further, to express an estimate of *degree of discrepancy* between presumed correlative coal beds, I have accepted Millott's estimate of the spore frequencies reported for the beds of the Potteries coal field as standard. The differences between the pairs of diagrams reporting spore frequencies for beds of the Cheadle field have been marked plus or minus for each step or grade of deviation in frequency from that Millott recorded in the Potteries area. This may serve accordingly as a rough but convenient index for evaluating the results, and by use of it we may gain greater insight into the evidence provided by the spore studies according to Millott's procedure. The degree of discrepancy can be suggested numerically with reference to any pair of analyses by simply adding the signs of plus and minus differences in reported frequency, and these figures are included (circled) on the chart.

Millott has reported frequency data on 24 spore types. Most of these can be roughly compared with generic groups utilized by Schopf, Wilson, and Bentall (*33*) as indicated in the column at the right. A specific comparison is out of the question, at least for the present, since the subtype differentiating characteristics are not very well presented in the literature. There is little question that species of *Lycospora* and of *Denso-sporites* dominate the assemblages and the specific differentiation of these various forms would be necessary for any more definite purposes.

Discrepancies in frequency are noted chiefly among the types poorly represented. It seems quite unlikely that all these differences should be accorded the same weight as correlational evidence. One would need to be immediately familiar with the various possible factors that could result in "absence" vs. "very rare" or "rare" occurrences, and it would be of the greatest assistance to have a better conception of the growth form and habit of as many as possible of the plants represented by these spores. One of the most likely causes for differences in minor representation can be imagined if the top or bottom layers of coal beds sampled in the two areas were not precisely correlative. If some

peaty accumulation continued in one location concurrent with a slight shift in composition of the flora and following cessation of peat deposition in the other area, the minor representation of some species represented in the spore residues could easily be influenced. A sampling of coal beds by lithologic layers so that the variations in dominance could be traced through the thickness of the coal bed, rather than by a completely mixed channel, probably would help to eliminate uncertainty arising from such causes.

Millott particularly notes similarities that appear at the Dilhorne-Cocks-head, Two Yard-Ten Foot and at the Crabtree horizons in the two coal fields, so it may be a question to what extent the more detailed work, as suggested above, is justified. By the method used in the diagrammatic presentation of Millott's results, comparison of assemblages from the Crabtree coal bed of the two areas is most striking, for only six discrepancies in frequency are noted in the recording of 24 items. Sixteen points of discrepancy are noted in comparison of the Winpenny and Foxfield coal beds. It is interesting to note that a lesser apparent discrepancy would be found in comparison of either the Winpenny with the Alex (10 frequency differences), and the same estimate of discrepancy is arrived at in comparison of the Bullhurst with the Foxfield. The least discrepancy, in fact, is obtained by comparison of the Alex with the Foxfield, both of the Cheadle field. Thus it is obvious that the simple superficial method of counting "discrepancies" used here is, by itself, of no significance in correlation; but it is hoped it will serve to direct attention more specifically to the variations and similarities in the spore assemblages from these beds. Probably an explanation of the differences would be forthcoming on further study of the coals in question, and such a study would doubtless contribute a significant chapter in the history of coal development at these particular horizons. The question involved is simply whether the flora contributing to the individual coal bed in the different localities is really as variable as it appears to be on general examination of the aggregate spore assemblages. Perhaps the most convincing basis for such work awaits more thorough botanical consideration of the forms that were differentiated as subtypes in the course of the British studies.

Information relative to the botanical understanding of fossil spore variation was presented by Dr. Leslie Moore in 1946 (23) through study of the forms disclosed in maceration of various sorts of coalified fructifications. This study is of considerable value in that it supplies further evidence of alliance for some of the common microfossil types found in coal residues. Indication that some of the common fossils now regarded as seeds (*Cordaicarpus*) may not have had that function also presents a fundamental problem of more general significance.

The original fossils were compressed in a shale matrix, and in several instances a number of sporangia apparently afforded enough material so that ontogenetic stages in development of spore ornamentation were interpreted. It may be well to point out that such an interpretation is difficult inasmuch as the argillaceous matrix also can provide associated spore forms of different types. Some of the examples notably different from the majority from a given fructification may have such an origin.

The results of this work have bearing on the difficult question of botanical affiliation of mature and characteristic isolated microfossils that would be identified if found in coal residues. The spore characteristics are so well shown in many instances that a comparison can be ventured even from drawings. Such comparisons cannot be accepted as indicative of specific or generic synonymy for several reasons, but there can be little question that the approach adopted by Dr. Moore affords information of general validity. The writer has summarized the comparisons that seem most evident in the tabulation below. Those in which some doubt of comparison exists are indicated as queried.

(a) 16 forms (plus 10?), from "sporangia," *Sphenophyllostachys, Corynepteris,* and *Senftenbergia* = *cf. Punctati-sporites.*
(b) 5 forms (plus 4?), from *Palcostachya* sp. and "sporangia" = *cf. Granulati-sporites.*
(c) 1 form (plus 4?), from *Sphenopteris* and smooth, glistening "sporangia" = *cf. Cirratriradites.*
(d) 8 forms, from "sporangium A" = *cf. Triquitrites.*
(e) 1 form (plus 7?), from *"Carpolithes ovoideus"* = *cf. Denso-sporites.*
(f) 5 forms (plus 2?, with spiral markings), from *Paleostachya* sp. and *Calamostachys* sp. = *cf. Calamospora.*
(g) 3 forms, from *Senftenbergia plumosa,* = *cf. Raistrickia.*
(h) 4 forms (plus 2?), from *Asterotheca oreopteridia,* and 1 form, from *Aulacotheca hemingwayi* (foreign?) = *cf. Laevigato-sporites.*
(i) 2 forms, from *Aulacotheca hemingwayi* = *cf. Monoletes.*
(j) 33 forms (plus 5?), from *Lepidostrobus* spp., *Sphenopteris,* and the smooth, glistening "sporangium" = *cf. Lycospora.*

A few further notes are required to clarify this tabulation. It will be evident that numerous forms upon which the writer did not feel competent to pass judgment have been omitted from consideration. Four of the five forms queried in comparison with *Lycospora* (j) are from the *Sphenopteris* and "sporangium" specimens. The judgment of comparison with *Raistrickia* (g) is based solely on ornamentation, a likely though somewhat questionable procedure, since the symmetry of these forms does not show. One wonders if the spiral markings shown by two forms compared with *Calamospora* (f) are indicative of an equisetoid character (elaters) at this early period of articulatean history.

It appears there is an indication here of the affinity of *Triquitrites* (d)—a suggestion of at least one kind of sporangium that bore them—and that this will serve to narrow the possible circle of affiliation. Some similar indication is afforded in the case of *Denso-sporites* (e), although question exists about the morphology of a number of the forms obtained by maceration of this example of *"Carpolithes ovoideus."* It is evident that *Lycospora* (j) is generally indicative of a concise lycopsid alliance. *Punctati-sporites* (a) was previously regarded (33, p. 29) as probably including elements of diverse affiliation, less useful on that account. It is still a question whether through more discerning study it may be restricted to a coherent group of plants. Both Radforth and Moore show that immature *Senftenbergia* spores are likely to be

classed according to their resemblance to *Punctati-sporites,* whereas, in some species of *Senftenbergia,* spores with mature ornamentation correspond with *Raistrickia.* If the immature forms ever occur abundantly in maceration residues as isolated fossils (rather than as aggregated masses), it is entirely possible that this alliance of schizaeaceous ferns would be reported in two separate species. Such an event, while it may be disconcerting to those unaccustomed to systematic treatment of fragmentary plant remains, still permits a reasonable reconstruction of ecological associations. A much greater danger lies in the indiscriminate aggregation of dissimilar elements in a single taxonomic species with the result that differences in composition of the floras are hopelessly obscured. There can be no superficial or easy approach to the complexities of this problem.

Although her contribution does not bear on the correlation of coal or on systematic treatment of microfossils, mention should be made of Miss Virkki's (now Mrs. K. Jacob) large treatise on spores from the lower Gondwanas of India and Australia (38). Ninety-seven different forms of microfossils are enumerated and briefly described and illustrated. Only a few are assigned to *Pityosporites.* The diversity of these microfossils in the Talchir boulder bed of the Salt Range and the Bacchus Marsh tillite in Australia provides strong evidence of a similarly diverse flora contemporaneous with Gondwana glaciation. Some of these no doubt represent groups of plants also represented in the Southern Hemisphere coal-forming floras.

An initial view of microfossils in Southern Hemisphere Paleozoic coals has been provided by Dulhunty (11). Forty-nine different "types" have been illustrated and described from the Permian of New South Wales. A very interesting cross-classification system was utilized in providing an artificial means of differentiation and designation. The simplicity and frank artificiality of the method are perhaps points to be considered in its favor if studies of botanical nature are infeasible. For local use in correlation, such studies may be of value, although the application is limited and probably will not provide a satisfactory basis for general inferences concerning coal deposition.

In classification, Dulhunty simply listed a considered series of prominent spore characters across the top and side of a cross-ruled sheet. The series of squares opposing the various sets of characters were numbered in sequence. Spores that happened to correspond with the characters thus arbitrarily combined take the type number of their particular square. Secondary differentiation is based on size and other features and indicated by a letter following the type number. It is interesting to note that several forms, his unusual type 21A, for example, are evidently highly specialized and as yet undescribed in any northern flora.

In a second paper the same author (12) records the distribution of the various spore types in 26 Australian coal beds, most of them in the Newcastle series of the Australian Upper Coal Measures. Spores were obtained abundantly from all coal beds except those in which rank advancement evidently interfered with their effective separation. Thirty-four of the types, as Dulhunty identifies them, appear common to all the beds and 14 appear to have

restricted ranges. Verification and explanation of these occurrences on a botanical basis would be of very considerable interest.

In a paper appearing the following year, De Jersey (9) continued the same system used by Dulhunty and applied it to study of spores from Queensland. Thirty-two types have been identified and described, each illustrated by a line drawing; six of these were not previously known from New South Wales. Descriptions of some of the Dulhunty types were modified slightly in line with observations of the new material. Samples derived from the Upper and Middle Bowen series, representing six coal districts, were investigated. Correlation with the Upper Coal Measures of New South Wales is suggested in four instances; two of these indicate inclusion within the Newcastle stage. Relatively few spores were present in samples from the Bowen bed of the Middle Bowen series, but it is suggested this characteristic, in itself, may have correlational value. In one instance only a very few unidentifiable spore fragments could be obtained from maceration. These preliminary studies probably will be of assistance in prospecting and developing the large areas of Permian coal measures in Queensland.

No attempt will be made to review plant microfossil work dealing with Quaternary peat and pollen analyses, as such, but mention should be included of a recent proposal for a form of artificial classification that evidently could be extended to cover pollens and spores of all ages, as well as certain other papers on Recent and Quaternary material important for general morphologic or ecologic reasons.

Erdtman (15) has proposed a new morphologic system of nomenclature and terminology to be generally applied to fossil pollen grains and spores. According to this proposal the morphological characteristics common to pollen grains and spores are to be formally codified and linked with a standard series of syllables or suffixes derived or abbreviated from roots of Greek and Latin derivation. These syllables would be combined to constitute a descriptive name corresponding in taxonomic nomenclature with the generic designation. A subordinate designation corresponding to a specific epithet would be added as a *"nomen differentiale";* an example of a name so constructed (*nomen imaginatum*) is *"Hexorites oblata."* Such entities would be called "sporomorphs" and thus technically distinguished from names of standard taxonomic usage.

In a later paper Erdtman (16) has given two examples of his "tentative terminology . . . to draw attention to 'sporoderm analysis' as an aid in palynological research." Two pollen forms of early Jurassic age are described that may indicate the presence of early dicotyledonous angiosperms. One with three furrows (*"Tricolpites* (*Eucommiidites*) *Troedssonii"*) may be allied with the Eucommiaceae; the other with a single furrow (*"Monosulcites magnolioides"*) has a "slight resemblance to the pollen grains in some magnolias." Erdtman makes it clear his names are without taxonomic status and apparently are to be interchanged freely to suit differing interpretations of morphology or relationship. Possibly they can be treated as having about the same status as the common names applied to garden plants, even though given in latinized form.

The present writer does not favor use of this system for several reasons. In the first place it seems inevitable that such names would further confuse taxonomy applied to fossil plants. All the artificial elements of a cross-classification system are present in it, as in the system used by Dulhunty (see above), and the superficial advantages of having "truly" descriptive names have long since been recognized as tending, in principle, toward nomenclatural instability. This is simply because scientists, like other mortals, are unable to foresee specific discoveries. A description that is relatively apt today ceases to be so when it is reconsidered some years later in the light of other findings. This is as true of the terminology peculiar to morphologic features as it is of the names of organisms. While nomenclatural stability is assured only by fixed association of a designation with reference to a nomenclatural type specimen, morphologic terminology is not and probably should never be as rigorously regarded. The intergradation of characteristics is a most significant biological phenomenon, and emphasis must be on *understanding the significance* of morphologic variations rather than on categorizing the variants according to formal concepts of their morphology.

While cross-classification systems appear to lend themselves to sciences, such as chemistry, that are amenable to more precise mathematical treatment, the best expression of botanical relationships is brought out by adherence to the biological classification methods (based on a hierarchical system) that have as their underlying unity the ideal of attaining a natural organization of the plant kingdom. Erdtman's proposal would result in mimicry of proper taxonomic names constructed in accordance with standard methods of taxonomy, however, the system behind these binomials (or trinomials?) would be altogether opposed to legitimate nomenclature in its fundamental conception. Use of a "binomial" nomenclature in this sense is not likely to relieve any one of the difficult and real problems in interpretation of plant microfossil materials, and it would contribute greatly toward a further needless confusion of issues.

If an artificial classification of plant microfossils is necessary or advisable to serve local and practical correlational purposes, it is much more appropriate that a system such as that employed by Dulhunty or by Raistrick or by Knox be devised, rather than that proposed by Erdtman, which the writer believes will be very widely misunderstood.

Shortly following Erdtman's proposal, Miss Cookson (4) also carried the "sporomorph" suggestion into execution in designating a new type of pollen grain from Oligocene-Miocene age brown coal in Australia. This form has been called *Tricolporites sphaerica,* and it now seems an open question as to how this name, properly constructed according to taxonomic principles of orthography but presumably of nontaxonomic implication, will have to be treated in relation to the regular nomenclature of plants. The same question arises concerning Erdtman's Jurassic angiosperm pollen.

In the same paper (4) Miss Cookson provides a very creditable study of fossil leaves from the same deposit, which she classifies as *Oleinites willisii.* A thorough comparative study of leaves of living members of the olive family rather adequately indicates their botanical relationship. One wonders why the fossil pollen forms are not given equivalent treatment. The ambiguous

status of sporomorph terminology seems to the writer chiefly significant as a fertile new source of nomenclatural confusion.

There seems to be no *a priori* reason for assuming that one sort of fossil material is less deserving of study than another, and one may suggest that, wherever pollen can be interpreted botanically, it is likely to have more widespread paleobotanical and geological significance than exceptionally preserved leaves which are much less common. In any event, it is hard to understand why isolated pollen grains should be called "sporomorphs" and classified artificially any more than isolated leaves should be called "phyllomorphs" and similarly treated systematically.

In an earlier paper Dr. Cookson (3) had been able to identify 10 species of *Nothofagus* from isolated pollen obtained out of the mid-Tertiary coals and sediments in southern and eastern Australia. The forms seem well characterized and recognizably differentiated in spite of variation and overlapping individual biocharacters, but Dr. Cookson has hesitated to provide specific epithets and refers only to the pollen-represented *Nothofagus* species by letters "A" to "J." Perhaps the evolutionary history of pollen and foliar features of the antipodal beeches will be easier to correlate through the Tertiary sequence than the writer supposes, and, if that is feasible, a fewer number of names, such as those already typified by leafy specimens, would suffice. One suspects, however, that if the problem is critically considered it will prove difficult enough, even when stratigraphic ranges are better defined, so that some nomenclatural distinctions between groups identified from leaves and those identified from pollen will always be advisable.

In an additional paper Miss Cookson (5) has adopted more orthodox systematic procedure in dealing with a considerable series of fossil "flyspeck" fungi (Hemisphaeriales) from the same and other Southern Hemisphere localities including the Kerguelen Islands. Six new genera and 11 new species are described with good botanical detail. All the groups named evidently are entirely suited for purposes of exact systematic reference, further taxonomic treatment, and whatever orderly revision is required to adjust the nomenclatural record in accordance with future discoveries.

The Hemisphaerialean material is of particular significance in that modern relatives of some of these fungi, at least, are restricted to highly humid tropical or semitropical climates. These climatic implications have much value in understanding the different conditions of Australian coal deposition during Tertiary time and with regard to Tertiary climate in a more general sense. It may be observed that the valuable deductions arising from this work are derived by understanding the botanical relationship of the plants. Such knowledge would not be available if they had been classified artificially (as "mycomorphs" (?)) without recognition of their affinity.

Fungus remains are often abundant in coal of Tertiary age, and some of the various types shown in thin sections have been illustrated and discussed by Schopf (31). More information than can be obtained from thin sections is needed for classification of these forms, but their occurrence and relation to degraded plant tissues are apparent.

The biology and taxonomy of certain saprophytic fungi of marine and brackish environments has been reported by Barghoorn and Linder (1) and is worthy of mention as an example of botanical work much needed to assist interpretation of fungi in coal and other fossil situations. Barghoorn contemplates further studies on the decomposition and preservation of submerged plant materials.

Almost all significant information about fossil fungi must be derived from microscopic study, and it is evident that, in relation to coal, they are important microfossils.

It is, of course, perfectly clear that information as to botanical relationships cannot be obtained uniformly through the great range of all the various types of microfossil structures. There is every reason, however, why natural relationships should be expressed *to whatever extent is possible*. Furthermore, there is no question that this information, whether scant or precise, can be accommodated, wherever classification is desirable, within the framework of the "natural system" of taxonomy. A question always arises as to what extent formal classification is necessary. Probably this can best be judged on the basis of the probable use of the fossils for age and ecological indicators.

Of greatest interest to students of Tertiary plant microfossils is the series of Olof Selling (34, 36, 37) dealing with the present and earlier Quaternary floras of Hawaii. Selling has restudied the pollen and spores of the modern Hawaiian flora and applied this information in interpretation of microfossils from peat. Perhaps the contribution of the greatest significance for those concerned with earlier floras is in regard to spores belonging to the Schizaeaceae, particularly those of species in the genus *Schizaea*, which are evidently widely represented in coals of Tertiary age. It is also noteworthy how often Selling discovered that previous information reported in the literature about pollen or spores of living species was wholly inadequate or erroneous. Additional studies such as these are badly needed to provide a better basis for interpretation of the various isolated microfossils of older deposits.

The same author (35) has also described a new species of *Triletes* of Mesozoic age from Hope Island, southeast of Spitzbergen. The material is present in a series of sections and consequently a little difficult to compare with forms normally isolated by maceration. The configurations in sections resemble those shown in microtome sections of *Selaginella* megaspores, but Selling believes they are more probably related to the Isoetaceae.

Triletes [5] as presently defined (29) cannot be restricted in affinity to any modern group smaller than the Lycopodiales, although if a familial assignment is required for this genus for taxonomic reasons, it might well be assigned to a new family of more generalized significance called the Triletaceae. The most important recent publication dealing with *Triletes* in its emended sense

[5] Selling (35) also mentions that Harris attributed *Triletes* to Reinsch's "Micro-paleophytologia" of 1884 rather than the "Neue Untersuchungen," which Reinsch published in 1881. Harris probably was following the writer of this review, who was apparently responsible first for this mistake. It is difficult to account for the bibliographic error at this time, but, in any event, it does not seem to have any bearing on the emended definition of the genus and its lectotype as selected in 1938.

is the monograph by Dijkstra (10) reporting work carried on in Holland during the war. A generally consistent taxonomic treatment has been adopted. Most noteworthy is the broader specific concept that Dijkstra has applied in a number of instances. *Triletes reinschi* Ibrahim, for example, is included as a synonym of *T. glabratus* Zerndt. It may be that these are closely related species and that the possible size range of these forms may not have been realized by many authors. However, Wicher (39) gave thorough consideration to this particular question, and he had access, at least, to Ibrahim's type material. Wicher reached the conclusion that the two forms are specifically distinct, and the reviewer is still inclined to accept his interpretation. Perhaps the question could be decided definitely if the holotypes of the species were brought together. Whether a broader or a narrower circumscription of *T. glabratus* is accepted, the taxonomic result is expressable as *"sensu* Wicher," or as *"sensu* Dijkstra." The type species of the genus is applicable whether *T. reinschi* is included as a valid species or as a synonym.

A more definite taxonomic criticism can be advanced against the transfer of *Triletes bennholdi* to *Cystosporites*. The latter genus is a member of the Lepidocarpaceae. There is good evidence that *Triletes bennholdi*, regardless of its unusual megaspore developments, was a free-sporing plant and thus has no close affinity to *Cystosporites*—certainly at the very best the relationship is extra-familial. Our knowledge of *Triletes bennholdi* is such that it can be referred only to a rather indefinite family, such as the Triletaceae. The publications in which the lepidocarp alliance was discussed (30) and in which *T. bennholdi* was referred systematically to *Triletes* (33) were evidently not available to Dijkstra. Perhaps he would have come to a different conclusion if he could have referred to these publications. There is no question that *T. bennholdi* diverges considerably from other species in *Triletes*, and it might be regarded as constituting a new section of the genus, or it may eventually be segregated as a distinct generic group. It does not in any case belong with *Cystosporites*.

Dijkstra also resurrects Kidston's Zonales (exclusive of the Triangulati) as a section of *Triletes*. The writer has himself long considered the advisability of such a taxonomic subdivision, but the evidence has not seemed clear and I suspect that two fairly distinct sectional alliances still are included in *sectio* Zonales as interpreted in a restricted sense by Dijkstra.

The Triangulati seem interpreted consistently by this Dutch author, although a question still remains concerning *T. gymnozonatus*. The two species of Zerndt that Dijkstra included in the new genus *Microsporites* have probably been allocated more satisfactorily in the spore synopsis (33, pp. 44, 45), where they were both queried but assigned to *Endosporites* and to *Cirratriradites*. Both of these forms are most appropriately studied by transmitted light. Zerndt's and Dijkstra's illustrations of *E. karczewskii* are not sufficiently clear to assuredly demonstrate the equatorial bladder of *Endosporites*, but the reticulation reported by Dijkstra is in keeping with such an interpretation. No such question enters in the case of *C. gracilis*. Dijkstra has not observed this form in Holland, but the same or a very closely related

species occurs in some upper Pennsylvanian coals of Illinois. Study of this material makes me question whether Ibrahim's *Sporonites radiatus* is closely allied with *C. gracilis*, as Dijkstra suggests. The former appears more probably referable to the triangulate section of *Triletes* as given in the Spore Synopsis (33, p. 24).

In addition to his taxonomic review, Dijkstra has presented important information about the stratigraphic distribution of forms found in the Dutch coal measures. Although the ranges of some species possibly might not have been as great if a narrower view of specific circumscription had been adopted, the results obtained are of much value. Nearly 100 coal beds, ranging in age from Namurian B to Westphalian C, were studied. Samples have been macerated according to the layer or bench subdivisions of nine coal beds, and these present a striking illustration of the inherent bench-by-bench variations in spore occurrence and frequency. Percentages as computed for the series of layers at each bed location are also similar enough in several instances to give convincing proof of the value of this information for correlations over short distances based on channel sampling. Occurrence data for each of 22 species are presented for all the beds. It is particularly worth noting that this information is presented in relation to the well-known stratigraphic succession of South Limberg, which is already regarded as a standard for more general correlation based on many other sources of evidence.

The only American study yet published comparable to Dijkstra's in stratigraphic scope is a publication by Cross (7), which is preliminary to a larger study still in progress. Cross's paper is not intended as a taxonomic contribution, but more than any other to date, it reports occurrences of types of spores through the American coal measures. General stratigraphic information is given for 28 *Triletes* species and varieties. The occurrence of several generic groups of smaller spores is mentioned for several coal beds. The paper is accompanied by numerous illustrations.

A shorter contribution was presented by L. R. Wilson (40) in description of a very singular group based on fossil spores that he named *Elaterites*. These forms were observed in uncompressed petrified condition in an Iowa coal ball of DesMoines age. Three loosely coiled perisporal(?) appendages, compared with elaters of *Equisetum*, occupy trimeridional sectors of the distal surface. The comparison with spores of *Equisetum* is not entirely convincing, and until more is known of these unusual forms possibly they should not be assigned to any order. The form is so distinctive that, unless the spiral appendages are lost in maceration, the group should be very easy to recognize in associations providing closer evidence of its affiliation.

A preliminary paper reporting the general results of a comprehensive survey of the smaller spores from Pennsylvanian beds of the Illinois basin has been presented by Kosanke (19). The stratigraphic distribution of genera has been discussed with regard to their value in correlation. A stratigraphic chart indicates the occurrence of genera and the frequency of specimens assignable to these genera irrespective of species. The extensive and detailed systematic report on these groups based on microfossils is now awaiting publication.

Kosanke indicates that a considerable number of genera show discontinuities in their stratigraphic ranges that are of definite value in correlation of Illinois coal beds. One ventures to hope that these discontinuities will eventually be explicable on an ecologic basis, possibly as a result of migration of elements of the successive floras. Information hinted at in this preliminary paper strongly suggests that the study, when completely published, will become a standard reference for detailed correlational problems in the area covered by the report.

CONCLUSION.

In closing this review, which has laid most emphasis on the systematic aspects of spore studies, I should like to present one final group of observations.

It appears that at the present time some indecision exists as to appropriate methods of microfossil classification. Those who have favored an artificial classification scheme for plant microfossils seem to have been influenced chiefly by the singular abundance of material. Those who have favored a more natural system of classification seem to have been influenced more by the evident botanical quality of some of the microfossil forms.

The reviewer believes one should not be dogmatic in condemning either point of view in its application to the various and varying purposes of coal work, although he has made no attempt to conceal his sympathy with those who prefer the latter viewpoint. Work in this important branch of micropaleontology still is in its primary stages, and a great deal of descriptive work must be accomplished before sound decisions on many matters of general significance can be arrived at. Under these circumstances it must be freely admitted that practical stratigraphic results may be achieved through extensive and rapid superficial studies that lack many botanical refinements.

It is fairly evident, nevertheless, that an evaluation of the ecologic conditions that govern coal accumulation and origin will have to be based to a considerable degree on some approximation of a "natural" understanding of the plants that have contributed to the coal beds. The groups of plant microfossils whose botanical relationships can be evaluated with some accuracy will contribute to this end. There can be little doubt, furthermore, that a greater reliance for stratigraphic and correlational purposes can be placed on forms that are understood botanically than on those having frequencies and ranges established on a more empirical basis.

It also is evident that this branch of paleontologic study, at this date, still is in its preliminary descriptive stages. Work is now being carried on in an encouraging number of recently established laboratories, both in this country and abroad, where the special techniques that are required can be extensively applied. Descriptive and taxonomic studies are likely to occupy the forefront for many years, simply because of the enormity of the new field to be explored. It does not follow that significant economic results will invariably follow initial exploratory studies; however, the history of paleontology in general is a sufficient insurance that reasonable benefits will come from progress in this work The plant microfossil record often is of special interest in

providing historical information about deposits that lack other types of suitable fossils. The pertinence of these materials to coal beds and coal geology is unique.

U. S. GEOLOGICAL SURVEY,
330 U. S. National Museum,
WASHINGTON 25, D. C.,
June 17, 1949.

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THE UTILIZATION OF INDUCED STREAM INFILTRATION AND NATURAL AQUIFER STORAGE AT CANTON, OHIO.[1]

RAPHAEL G. KAZMANN.

ABSTRACT.

The program of engineering exploration and the quantitative study of ground water storage and recharge to assure Canton, Ohio, of a permanent ground water supply of predetermined magnitude are summarized herein.

Two completely separate aquifers, one underlying the other, were found in the area. A pumping test was made in each formation and the results were used as a basis for determining the number and type of horizontal collectors needed to develop 10 mgd of firm water. This necessitated the design and construction of dual-purpose collectors to infiltrate up to 18 million gallons per day from a small, nearby stream at all times. Because it is a pioneer installation, the Ohio Water Resources Board, the City of Canton, and the U. S. Geological Survey are making a careful study of the collector field as it continues to operate. Preliminary data indicate that the system was conservatively designed and will probably yield more water than was originally expected.

INTRODUCTION.

CANTON, Ohio, is located on the former junction of several preglacial streams whose valleys have since been filled by glacial outwash materials intercalated with layers or lenses of clay. On the basis of previous work done by the Ohio Water Resources Board and the U. S. Geological Survey, evidence was available of the existence of a buried valley underlying part of the West Branch of Nimishillen Creek.[2] The contours of the bedrock surface of the preglacial valley and its relation to the stream are shown in Figure 1.

THE PROBLEM, GEOLOGIC AND HYDROLOGIC.

In the fall of 1946 the City of Canton indicated its willingness to finance a hydro-geologic survey to determine the perennial quantity of water, if any, to be obtained by infiltration from West Branch of Nimishillen Creek. Exploratory holes were drilled to determine the actual position of the buried valley and the types and thicknesses of the materials composing the aquifer. Meanwhile an investigation of stream flow characteristics was started. It was found that no stream flow records were available for the West Branch of Nimishillen Creek whose drainage area is 37 sq. miles.

[1] Presented before the Society of Economic Geologists, San Francisco Meeting, February, 1949.

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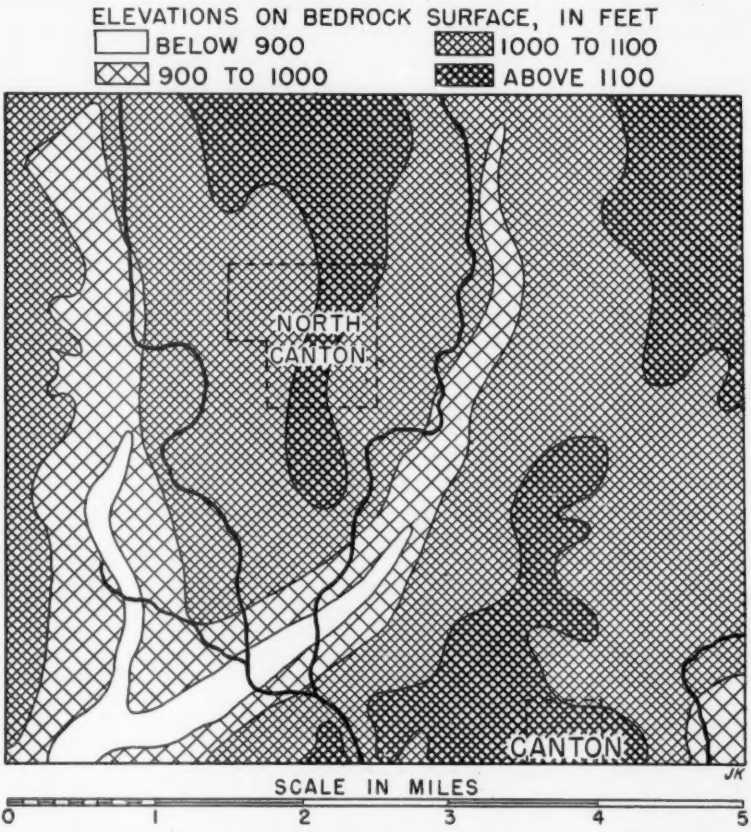

Fig. 1. Elevation of the preglacial bedrock surface, showing the relationship of the buried valleys to the forks of West Branch, Nimishillen Creek.

STREAM FLOW AND ITS RELATIONSHIP TO THE AREAL GEOLOGY.

Studies in Ohio had previously established that the dry-weather flow characteristics of Ohio streams are primarily determined by the surficial geology of their drainage basins. Although no records were available for the West Branch of Nimishillen Creek, a good, long record was available for nearby Sandy Creek. In 1941 the Ohio Water Resources Board had published a flow-duration table for Sandy Creek. This table (which can be plotted as a curve) is the statistical analysis of daily flow quantities grouped by the numbers of days in which each flow rate is equalled or exceeded.

C. V. Youngquist, Chief Engineer of the Ohio Water Resources Board, suggested that, since the geology of the stream basins was approximately the same, simultaneous gagings be made on Sandy Creek and West Branch and the results compared on the basis of cfs per square mile of drainage area. Thus it would be possible to determine whether or not the stream flow record of Sandy Creek was comparable to that of West Branch. This suggestion was

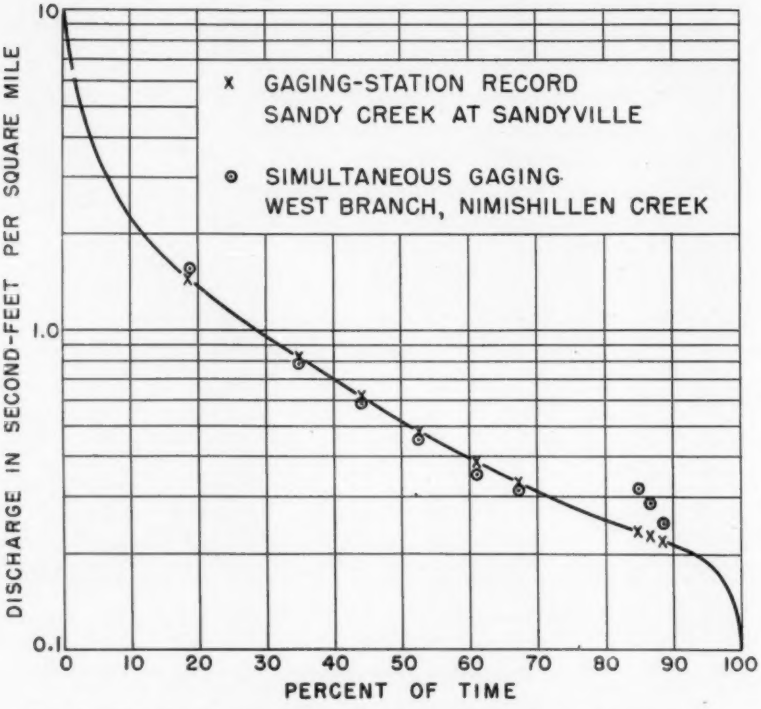

FIG. 2. Flow duration curve of Sandy Creek with simultaneous measurements of West Branch, Nimishillen Creek plotted for comparison.

carried out and the characteristics of West Branch were found to be almost identical to those of Sandy Creek, meaning that an equal amount of water would be available per mile of drainage area of West Branch as was available for Sandy Creek. This meant that it would be possible to use the flow characteristics of Sandy Creek to compute the flows of West Branch. The flow-duration curve of Sandy Creek and synoptic measurements on West Branch are shown in Figure 2.

GEOLOGIC EXPLORATION.

The exploratory work proceeded satisfactorily and revealed that instead of one continuous aquifer in the valley there were two, one underlying the other. Apparently after the first period of outwash, a glacial lake had formed in which fine sediments settled. Later, when the glaciers melted, a new stream had eroded a channel in these clayey deposits, later depositing sand and gravel in the eroded channel. However, the clay layer had not been eroded through and

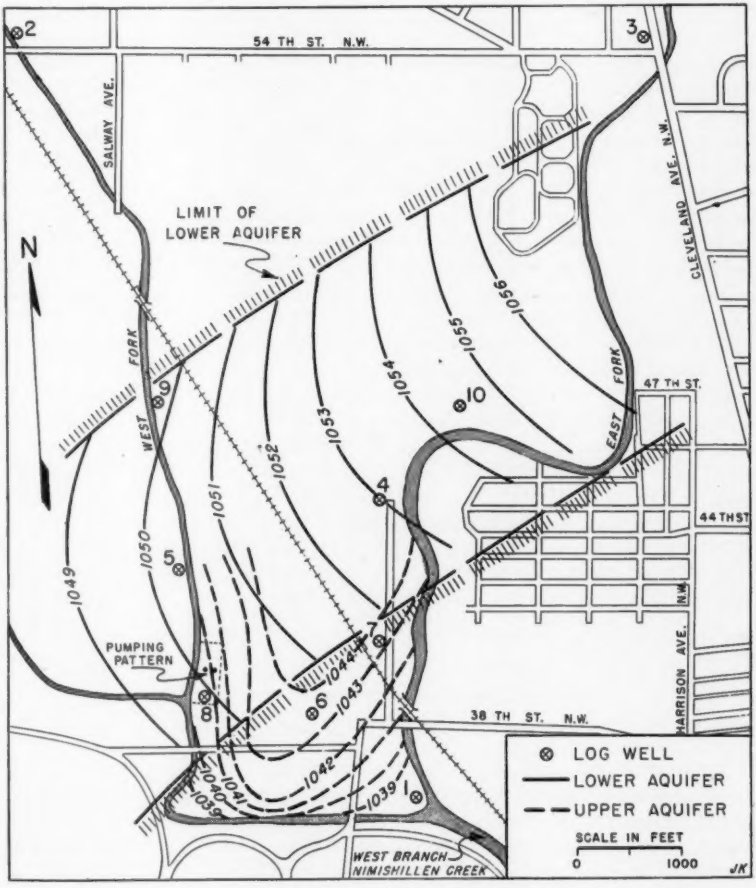

FIG. 3. Water level elevation map of explored areas. Two distinct patterns of contours means two separate aquifers.

the aquifers were separated by clay throughout the area explored. This complete separation of aquifers was indicated by the well logs, substantiated by waterlevel contour maps drawn on the basis of observation well measurements in the area (Fig. 3) and conclusively proven by means of two pumping tests, one in the lower material and one in the upper.

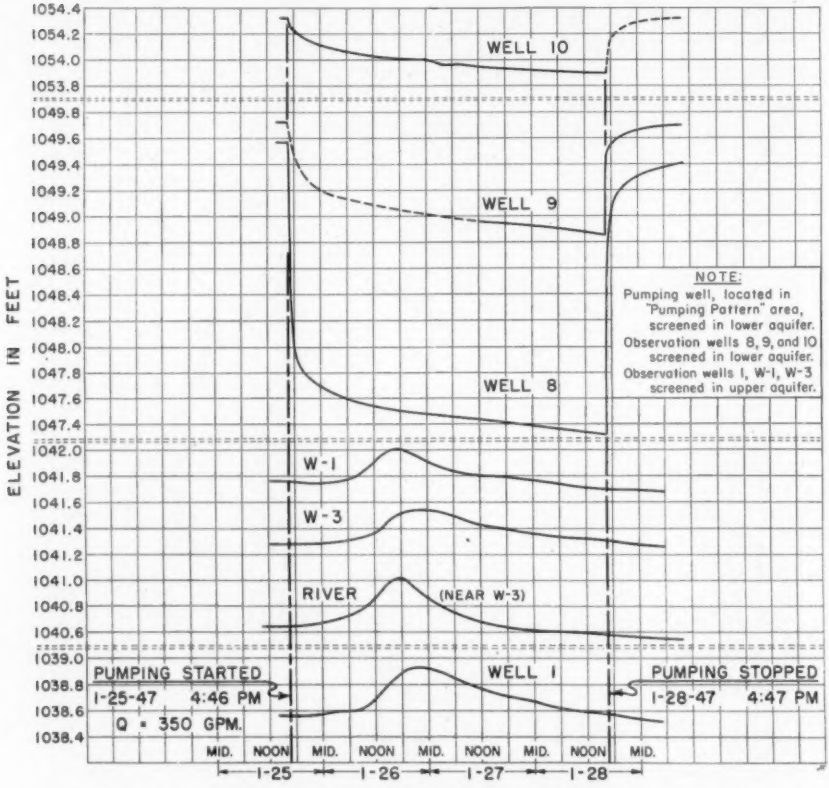

FIG. 4. Hydrographs obtained during pumping test on lower aquifer. No pumping effects noted in upper aquifer.

The pumping test in the upper aquifer proved that water from West Branch would infiltrate to the aquifer in response to hydraulic gradients produced by pumping wells. The effective coefficient of permeability was also obtained from this test.

A pumping test in the lower aquifer, that is, the aquifer below the clay layer, gave figures for effective permeability (about twice as high as those ob-

tained from the upper aquifer) and demonstrated the effectiveness of the clay separation. Figure 4 shows hydrographs obtained during the pumping test on a well tapping the lower aquifer. It is of interest to note that a well in the upper aquifer located only 100 feet from the pumping well showed no response to pumping while a deep observation well 3,500 feet away showed a sharp, measurable decline of over 0.3 foot. All measurements were obtained by the use of automatic water stage recorders.

THE WATER SUPPLY PROBLEM ANALYZED.

Upon study it became clear that to tap the upper aquifer alone was a fruitless proposition. The stream flow was very small during the summer and due to the small thickness of the upper aquifer there was insufficient storage to provide for periods of low flow.

It was equally fruitless to tap the lower aquifer. Although plenty of water was available in storage there was no clearly determinable source of recharge. It could be shown that this aquifer would be exhausted by any considerable pumpage, say in excess of 3 mgd.

Some method had to be found to connect the aquifers in such a way that the water in storage which was withdrawn from the lower aquifer would be replaced from the upper aquifer during periods of high stream flow. The first step was to analyze the situation in general terms, assuming adequate reservoir capacity in the lower aquifer and certain maximum rates of replenishment.

It is important to note that in filling an aquifer by the infiltration of surface water the maximum inflow rate is only a fraction of the maximum stream flow. In a comparable surface reservoir the whole flow of the stream can be impounded until the reservoir is full. This means that the infiltration rate through the stream bed is the "bottleneck" which prevents the bottle from being filled as rapidly as the water becomes available.

At the request of the City of Canton, to provide water for a stream traversing a park, 4 mgd of flow was reserved for stream flow purposes below the aquifer area. With this in mind the flow-duration table for West Branch was recomputed to show the average quantities of water available for infiltration during various periods (Table 1).

TABLE I.

FLOW DURATION OF WEST BRANCH OF NIMISHILLEN CREEK.

Number of days	Average useful flow in mgd	Number of days	Average useful flow in mgd
4	192	36	16
4	164	36	10.8
4	122	36	7.3
4	103	36	4.9
8	85	18	3.3
8	69	18	2.5
8	58	18	1.7
18	46	18	1.1
18	34	8	.6
18	27	8	.3
18	21	21	0

Each year during an average period of 180 days, the effective flow is less than 10 mgd and all or part of the water pumped must come from storage. Assuming that the maximum rate of infiltration can be fixed and the storage is adequate, a graph can be drawn, based on the flow-duration curve, showing the

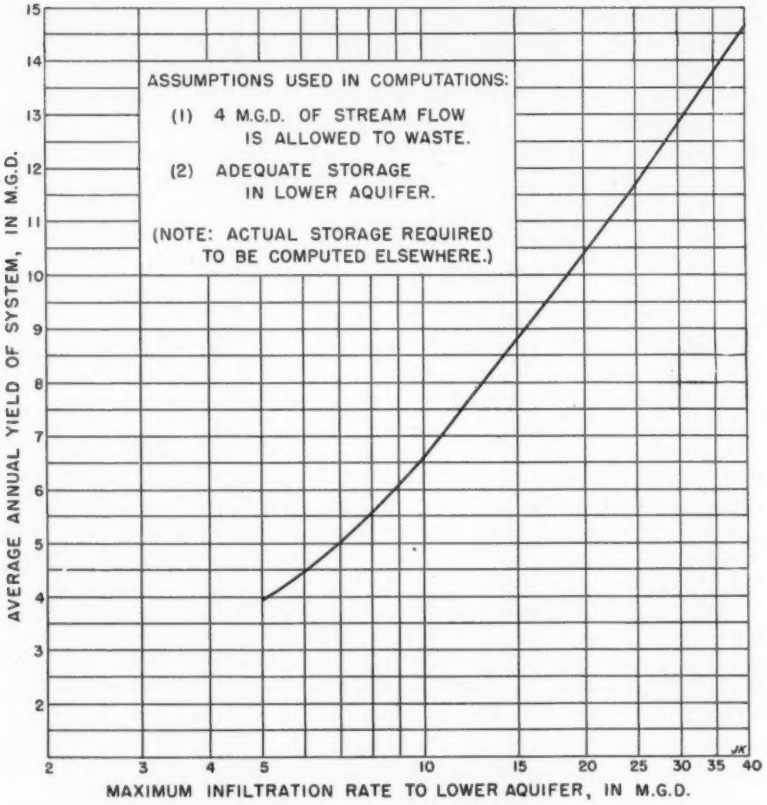
ASSUMPTIONS USED IN COMPUTATIONS:
(1) 4 M.G.D. OF STREAM FLOW IS ALLOWED TO WASTE.
(2) ADEQUATE STORAGE IN LOWER AQUIFER.
(NOTE: ACTUAL STORAGE REQUIRED TO BE COMPUTED ELSEWHERE.)
AVERAGE ANNUAL YIELD OF SYSTEM, IN M.G.D.
MAXIMUM INFILTRATION RATE TO LOWER AQUIFER, IN M.G.D.
2 3 4 5 10 15 20 25 30 35 40
2 3 4 5 6 7 8 9 10 11 12 13 14 15

FIG. 5. Perennial yield of Canton's new water supply system in terms of collector infiltration capacity.

firm yield of the area for any given maximum rate of aquifer replenishment (Fig. 5). It shows that, assuming the storage is available, 10 mgd can be obtained at all times if a peak infiltration rate of 18 mgd is possible. The aquifer storage necessary to support a withdrawal of 10 mgd is computed to be 1.1 billion gallons.

THE SOLUTION OF THE PROBLEM.

The survey work and hydro-geologic analyses having been completed, the requisites for a successful engineering job were: that structures should be built capable of producing 18 mgd from the upper aquifer when the water is available, and these structures should be able to put this water into the lower formation when its storage has been depleted. These structures should also be capable of producing 10 mgd from the lower aquifer and, if needed, should be capable of dewatering it a minimum of 40 feet for a distance of 15,000 feet measured along the axis of the valley. Such a dewatering operation would yield from

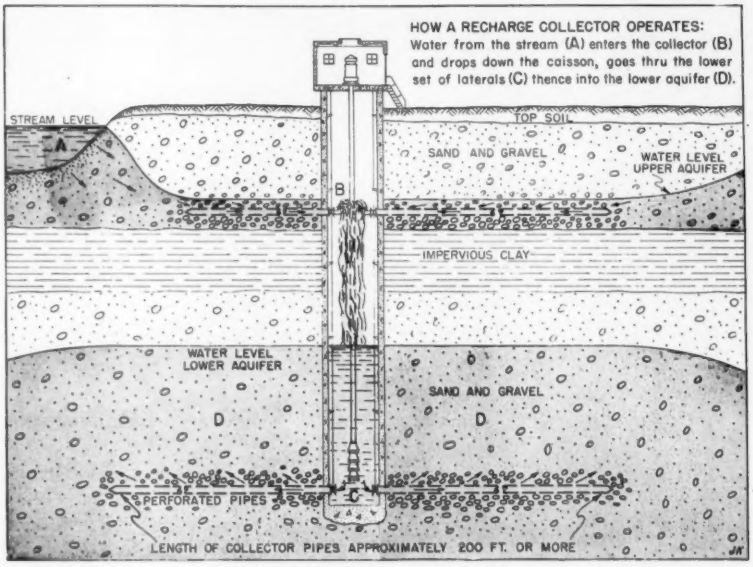
HOW A RECHARGE COLLECTOR OPERATES:
Water from the stream (A) enters the collector (B) and drops down the caisson, goes thru the lower set of laterals (C) thence into the lower aquifer (D).
STREAM LEVEL
A
TOP SOIL
SAND AND GRAVEL
WATER LEVEL UPPER AQUIFER
B
IMPERVIOUS CLAY
WATER LEVEL LOWER AQUIFER
SAND AND GRAVEL
D
D
PERFORATED PIPES
C
LENGTH OF COLLECTOR PIPES APPROXIMATELY 200 FT. OR MORE
JM

FIG. 6. Schematic cross section through Canton's dual-purpose pumping collector.

storage a minimum of two billion seven hundred million gallons, sufficient for 9 months of zero stream flow, and enough to allow a generous safety factor to compensate for any hydrographic uncertainties.

The solution of the problem involved building three dual-purpose horizontal infiltration collectors with a total maximum infiltration capacity of 18 mgd. One of these dual units was designed to be built deep enough to act as the supply unit and was equipped with suitable pumps. The other two were designed to replenish the lower aquifer as it became depleted and have no pumps installed in them. Figure 6 shows the construction and method of operation of a dual-purpose unit.

The installation was built as planned. The firm capacity of the field, treated as an infiltration-recharge plus subsurface storage system, is computed to be 10 mgd. The actual capacity may be greater because in arriving at the 10 mgd figure the underflow in the lower formation was neglected, since it was

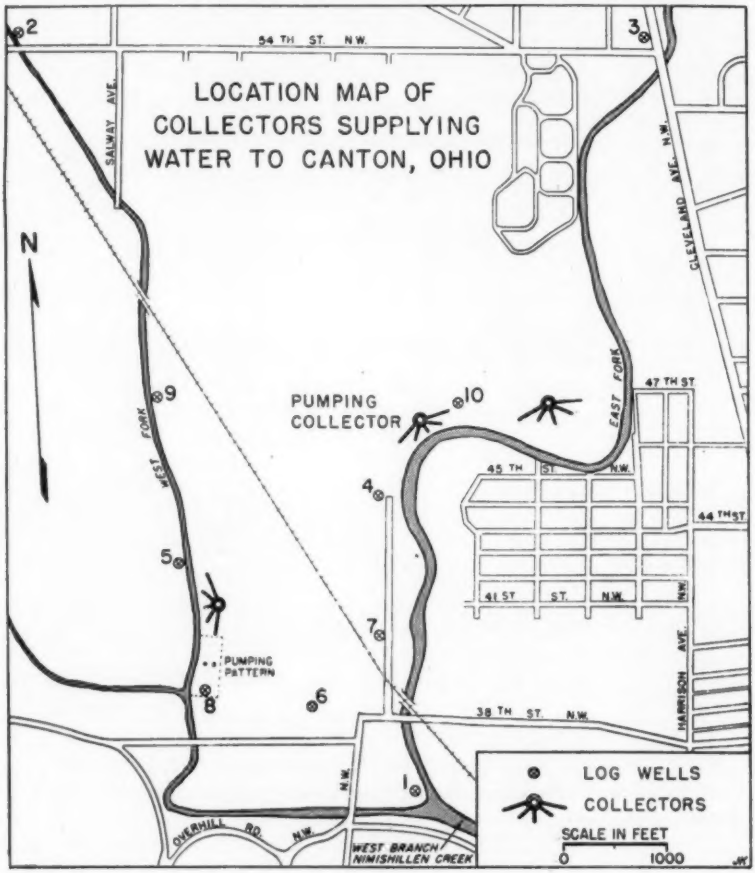

FIG. 7. Location of collectors comprising Canton's new source of water.

not possible to determine its magnitude during the brief survey period. As explained previously 4 mgd of stream flow is allowed to waste (but would be available in event of need); rainfall recharge to the upper aquifer was neglected, as no long-term water level records were available; and there are indi-

cations that the stream flow records used in computing infiltration quantities were actually conservative. Figure 7 shows the location of the completed collectors.

In view of these "plus" factors, it was recommended that a pumping capacity of 15 mgd be installed and utilized in the deep, pumping collector; that a series of weirs with automatic recording gages be installed and operated in the area, and that the observation wells put down in the course of and after the termination of the exploratory work be measured periodically for the maintenance of a running inventory of the water entering and leaving the water supply area. These recommendations are now being carried out (1949). After several years of heavy pumpage, the observations of stream flow and water levels will yield a better figure as to the magnitude of perennial supply than the conservative engineering figure reached as a result of the original survey.

OPERATING DATA.

Although the collector system was completed in March, 1948, it was put into operation only after the arrival of pumps and the completion of the connecting pipe line in July, 1948. However, some interesting data have already been accumulated as the result of the cooperative program carried on by the City of Canton, Ohio, the Ohio Water Resources Board and the United States Geological Survey. Seepage runs have been made on that fork of West Branch already affected by pumping. During a period of low flow in the fall of 1948 about 50 percent of the water flowing in the fork was infiltrated, although water levels had been drawn down under only part of the expected area of infiltration, due to the briefness of the period of pumping.

That almost 50 percent of the stream flow could be infiltrated at low flows may be somewhat surprising but is in accord with experience on the Middle Branch of Nimishillen Creek which feeds the now unused Northeast field.[3]

It is believed that this dual-purpose installation at Canton, Ohio, is the first ground water supply in the world built in a virgin ground water area, which was designed to operate utilizing a designed, but variable rate of aquifer recharge in combination with a predetermined volume of natural subsurface storage to produce a predetermined quantity of "firm" water.

CONCLUSION.

The studies described above point the way to hydrologic engineering which will utilize the predetermined storage of aquifers in conjunction with stream flow and infiltration data to produce permanent ground water supplies of given magnitude. In considering sites for water storage, the hydrologic engineer and the economic geologist should not overlook rechargeable aquifers. In contrast to surface water reservoirs, the losses from storage aquifers due to evaporation and transpiration are negligible and there is no lessening of storage due to silting; nor is valuable land removed from productive uses through flooding.

[3] Van Tuyl, D. W., Losses in Streamflow Caused by Pumping Ground Water at Canton, Ohio: U. S. Geol. Survey, Water Resources Bulletin, pp. 57–59, May 1948.

ACKNOWLEDGMENTS.

The work described above was performed by Ranney Method Water Supplies, Inc., of Columbus, Ohio, and the permission to publish the data obtained by the Company is gratefully acknowledged. The whole project was executed under the technical direction of Eugene W. Silitch, President of the Company. Construction was done under the supervision of A. d'Audiffret, Vice President and Chief Engineer, and the test drilling and pump testing was accomplished under the supervision of Robert E. Reimund, Superintendent of Surveys. The writer is indebted to Messrs. Silitch and d'Audiffret for their criticism and suggestions in preparing this paper. The drawings were prepared by John Krolcyzk.

RANNEY METHOD WATER SUPPLIES, INC.,
COLUMBUS, OHIO,
March 10, 1949.

SOME OCCURRENCES OF CHROMITE IN NEW CALEDONIA.

JOHN C. MAXWELL.

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ABSTRACT.

The deposits described are steeply dipping tabular masses of disseminated chromite in serpentinite, with or without associated blocks and sack-form bodies of massive chromite. At La Coulee and Chagrin the deposits show an irregular alternation of chromite-rich and chromite-poor layers parallel to the walls of the ore body. Where present, massive chromite bodies tend to be oriented with their long axes in the plane of the layering.

Much of the chromite is intermixed with and surrounded by a thin margin of yellowish green serpentinite which grades outward into the darker green to greenish black serpentinite of the country rock. Chromite grains disseminated in the yellowish green serpentinite commonly have black opaque borders and are less translucent and more magnetic than massive chromite in the same deposit. It is postulated that iron oxides, set free during serpentinization of olivine, migrated to nearby chromite grains, thus enriching the chromite in iron and leaving the adjacent serpentinite iron-poor and lighter in color.

The manner of occurrence indicates the chromite was carried in as solid masses and crystals during emplacement of the ultramafic host rock. Late movements resulted in shearing and fracturing of ore bodies and country rock; serpentinization accompanied or followed the shearing.

INTRODUCTION.

THE writer was stationed in New Caledonia with the United States Navy from January, 1944, until August, 1945, and was able to study some of the nickel and chromite occurrences, particularly in the southern part of the island. The nickel deposits have been treated in a number of papers, the

most recent by E. de Chetelat (1).[1] In spite of the importance of the New Caledonian chromite, very few descriptions of individual deposits have been published. It seems worthwhile, therefore, to record the writer's observations even though they are somewhat of a reconnaissance nature.

GEOLOGIC SETTING.

The geology of New Caledonia has been treated at length by Piroutet (2) and a summary of the geology including a brief description of the mineral

FIG. 1.

deposits is given by Glasser (3). Since neither paper is readily accessible to readers in this country the following summary, taken mainly from Piroutet, may be helpful. The rock types and sequence of events are believed to be reliable, though some of the geologic ages are questionable.

In the central and northern part of the island a crystalline complex of unknown age, consisting of mica and sericite gneiss and schist, glaucophane schist and amphibolite, forms the basement. It is overlain by unfossiliferous sericite schists and quartzites assigned by Piroutet to the Algonkian or older Paleozoic. Presumably the area was deformed and uplifted following the

[1] Numbers in parentheses refer to bibliography at end of paper.

deposition of the "Algonkian" sediments, for these are said to be overlain unconformably by fossiliferous Permo-Triassic beds characterized by littoral deposits (shales, graywackes, conglomerates) and rhyolite and andesite flows and tuffs on the west coast and by fine-grained ammonite-bearing shales in the central and eastern part of the island. A second period of folding and uplift followed.

Toward the end of the Jurassic there was another submergence of the island, this time beginning in the south-southwest. Deposition, continuing with minor interruptions until late Cretaceous time, was characterized by clastic sediments with intercalated coal beds. The early Cretaceous strata also contain numerous flows of andesite and rhyolite. Following the deposition of the late Cretaceous beds the island was once more subjected to folding and uplift.

In middle Eocene the island was again flooded from the southwest, and shale, impure limestone, and conglomerate were deposited, intercalated with abundant andesitic and basaltic flows and tuffs. The fourth and last period of folding and uplift occurred after middle Eocene. At this time, presumably, the great ultramafic masses were intruded, as were minor amounts of feldspathic rocks, gabbro, diorite, etc. Miocene beds are said to overlap the ultramafic rocks in the south of the island (4).

Chromite occurs only within the ultramafic rocks or in placers derived from them. The ultramafics which occupy more than a third of the area of New Caledonia (Fig. 1), consist largely of dunite and harzburgite, more or less altered to serpentine. Feldspar-bearing rocks, principally norite, are present but quite rare (5). Only two occurrences of such rocks were seen by the writer; one is a hornblende gabbro dike in the La Coulee chrome mine, to be described later, the other is a rather large norite mass of undetermined shape exposed for about 1½ miles along the coast, 2 miles east of Plum and 14 miles east of Noumea. In both cases the feldspathic rock is younger than the serpentinized peridotite. Near the norite body, veins and masses of coarse but badly weathered hornblende-quartz-feldspar pegmatite are found in both the peridotite and norite.

PREVIOUS WORK.

The magnitude and possible importance of New Caledonia's chromite deposits was early recognized by Garnier (6). Mining actually began in 1878 and a considerable number of deposits, both lode and alluvial, were soon brought into production. A brief description of many of these earlier workings is given by Glasser (7); more recent developments are discussed in a later paper (8). Papers by Powers (9), Blanchard (10), and Fisher (11) contain additional information on New Caledonian chromite.

CHROMITE DEPOSITS.

The chromite deposits occur chiefly in two areas, namely southern New Caledonia, and in Tiebaghi dome. Four deposits of the southern area are discussed and one from Tiebaghi (Chagrin).

La Coulee.—This deposit is located 10 miles east northeast of Noumea, about a mile northwest of the Mt. Dore-Yate road and two miles north of the junction of that road with the Noumea-Plum road. It was mined by open cut and is now inactive. Exposures of the ore body in the walls of the cut indicate it is essentially tabular, about 5 to 6 feet thick, more than 85 feet long, striking 115° true and dipping 40° southwest.

The ore occurs in yellowish green, partly serpentinized dunite while the over- and underlying rock, also partly serpentinized dunite, is greenish black, as are most of the ultramafic rocks. The upper boundary of the chromite-bearing yellow serpentinite [2] is quite sharp (Fig. 2). The lower boundary is mostly covered but appears to be sharp also.

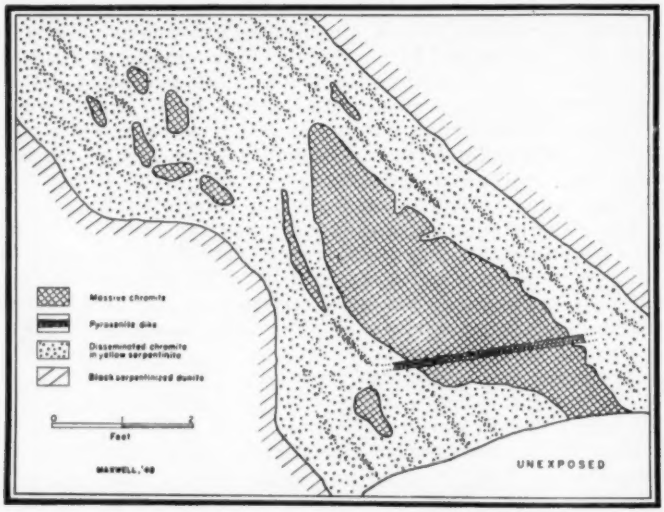

FIG. 2. Southeast wall of open cut, La Coulee.

Chromite occurs as fine disseminated grains within the serpentinite (*chrome pique*), and as thin lens and small blocks and sack-form masses. The disseminated grains average about half a millimeter in diameter, but chromite in the lenticular and blocky bodies is coarser grained (5mm±), brilliant black, with a sub-conchoidal fracture. Serpentine-filled fractures lace the chromite masses. Most of the lenticular masses are elongated in the direction of the strike of the ore body and flattened parallel to its upper and lower contacts. The sack-form masses are irregularly oriented (Fig. 2) though the longest dimension of many of them is approximately parallel to the dip of the ore body.

[2] In this paper serpentine refers to minerals, serpentinite to rocks which contain more than 50 percent of the various serpentine minerals.

In thin sections the chromite of the ore body is deep red-brown, grading to yellow brown in thin edges. Many of the grains show black opaque borders; cracks crossing the grains commonly have similar black margins. The grains are somewhat rounded as though they had been corroded by the olivine matrix, but part of the olivine crystallized earlier than the chromite for minute inclusions of unaltered olivine are found in chromite grains.

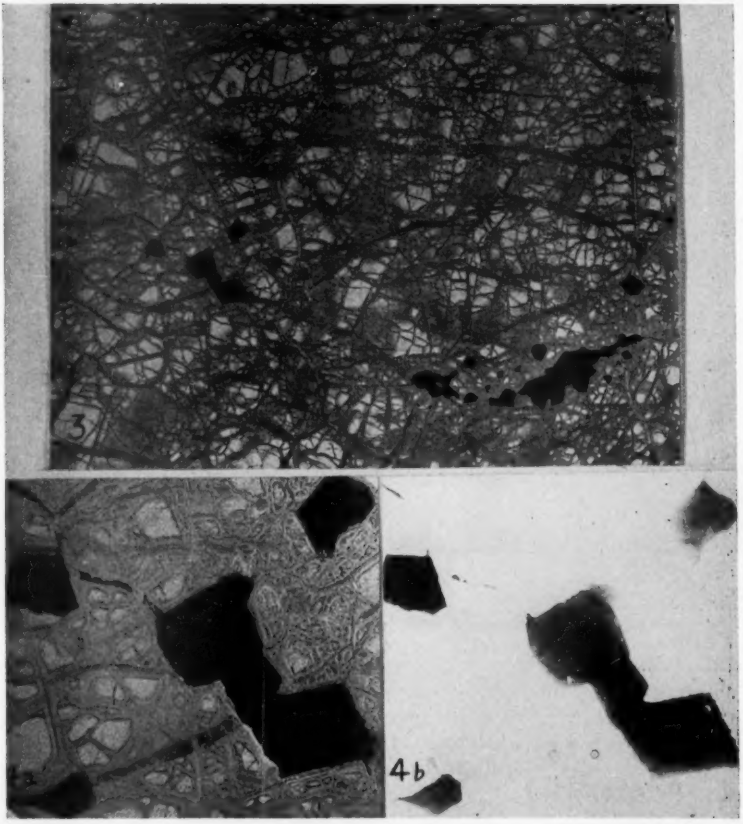

FIG. 3. Chromite grains in partly serpentinized dunite wall rock, 4 feet above the ore body, La Coulee. Note cuspate extension of chromite grains along serpentine veinlets carrying dusty magnetite. × 9.

FIG. 4. Enlargement of left central portion of Figure 3. 4a shows dusty magnetite in veinlets and around grain margins; 4b, taken with longer exposure, shows translucent chromite grains with partial black borders and crossed by black lines. × 30.

The olivine is colorless, with 2V about 90°. It alters to nearly colorless serpentine with low birefringence and mesh structure, and lacks the dusty magnetite of the dark, serpentinized dunite described below.

A specimen of greenish black dunite, collected four feet above the ore body, contains scattered chromite grains and is about half altered to serpentine. Where serpentine replaces the interior of olivine grains it is pale greenish gray in color and nearly isotropic; veinlets of cross-fiber serpentine, many containing arborescent and dusty magnetite [3] in their centers, outline and

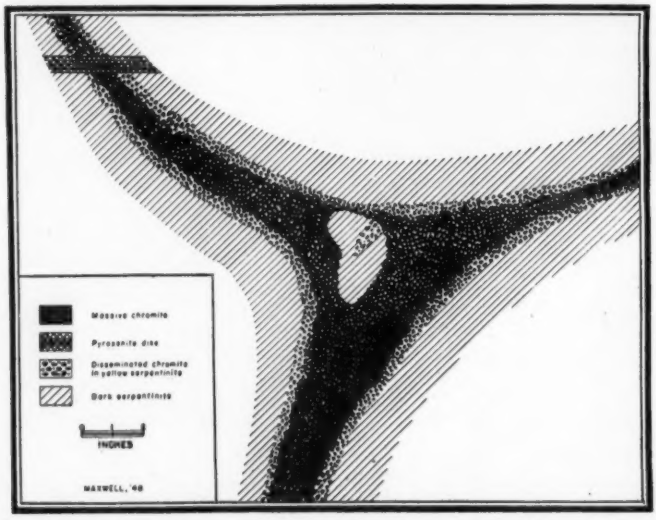

FIG. 5. Sketch of branching chromite dike exposed on vertical face of serpentinite mass in bottom of La Coulee open cut. Serpentinite is in place.

cross cut the olivine grains. The chromite grains are dark brown to black and opaque, lighter brown and translucent on thinest edges. Some are euhedral and appear to have been included in olivine crystals, others occur in strings of cuspate grains arranged along olivine grain boundaries (Fig. 3). Dusty magnetite fringes many of the chromite grains which also tend to have black opaque margins around parts of the grains and along cracks crossing the grains (Fig. 4).

In the country rock above the ore body occur dike-like bodies of chromite and *chrome pique* with steep to vertical dips, and strikes more or less at right angles to that of the ore body. In no case was it possible to determine whether the chromite "dikes" were actually offshoots of the ore body but proximity suggests they are. One of the "dikes" (Fig. 5) is Y-shaped and consists

[3] The material identified as magnetite is very fine grained, black, opaque on thinnest edges and strongly magnetic.

largely of massive, coarse grained, shiny black chromite with some *chrome-pique*, mostly along the edges. The "dike" has a thin (5mm±) selvage of yellowish green serpentinite which grades rather abruptly into the dark gray-green serpentinite of the country rock. The chromite of the "dike" resembles that of the ore body. Disseminated grains at the margins average about a half millimeter in diameter while the more massive chromite is coarser grained, shiny black and shot through with serpentine-filled fractures. In thin section (Fig. 6) the disseminated chromite grains of the *chrome-pique*

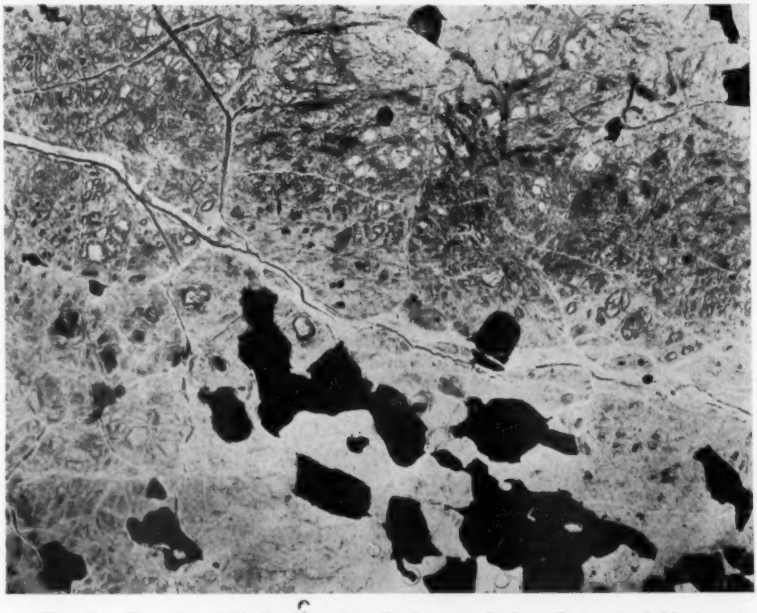

FIG. 6. Chromite "dike" above La Coulee ore body. Contact of black serpentinite of wall rock with yellow serpentinite and disseminated chromite of the dike. Note dusty magnetite of serpentine veinlets in wall rock (top) and scarcity of magnetite in similar veinlets within the disseminated chromite area (bottom). × 12.

margins are anhedral and appear to be strongly corroded. The grains are nearly opaque with dark brown centers and commonly with black margins and cross-cutting black lines. Fringes of dusty magnetite are common, especially on isolated grains furthest away from the massive chromite. Many of the grains show cuspate projections of the black, opaque borders and these are partly responsible for the corroded appearance of the grains. In the isolated opaque grains the cuspate projections extend into serpentine veinlets carrying abundant dusty magnetite (as in Figs. 3 and 4) and the grains themselves

FIG. 7. Ernoule prospect showing outline of chromite block. Surface marked F is a small fault. Photo by Haley Houghton.

FIG. 8. Ernoule prospect. Nature of contact of chromite body with serpentinite of the wall rock. Photo by Haley Houghton.

show fringes of the magnetite. The dusty magnetite is abundant only in the darker serpentinite. In the lighter colored serpentinite fringing the chromite dusty magnetite is practically absent, but the chromite grains have opaque to very dark brown cuspate projections pointing along serpentine veinlets similar to those carrying dusty magnetite in the darker serpentinite (Fig. 6). In thin section no definite boundary can be found between the light and dark serpentinite; they seem to be identical except for the abundant dusty magnetite in the latter.

Coarse grained pyroxenite pegmatite dikes are present in both the country rock and the ore body (Figs. 2, 5). Pyroxenite pegmatite cutting the chromite "dike" consists largely of coarse crystals of enstatite, with scattered grains of dark brown, translucent, corroded chromite arranged along the grain boundaries. Enstatite has been partly altered to bastite at the contact with serpentinized wall rock and along cross-cutting fractures. A coarse grained gabbro pegmatite dike one inch wide was observed in the country rock 8 feet above the ore body and parallel to it. This dike rock is badly weathered. The pyroxene is enstatite but the feldspar is indeterminable.

On the south wall of the open cut near the west end, a vertical one-foot dike of fine grained hornblende gabbro cuts the dunite above the ore body and presumably also cuts the ore body at depth. The dike is broken into polygonal blocks by well developed joints perpendicular to the dike walls. The rock contains about 75 percent hornblende, strongly pleochroic in shades of brown and tan, and more or less altered to bright yellowish green serpentine; the remainder is fresh sodic bytownite, strongly twinned but unzoned.

Ernoule.—On the east flank of Mt. Dore a prospect pit has been opened in a small chromite mass, 50 yards west of the Noumea-Plum road and 2.8 miles southeast of the bridge where that road crosses the Boulari River. The chromite body appears to be an irregular block with its largest dimension east-west, dipping 80° south. A small fault cuts the chromite near its western margin (Fig. 7). The inclined prospecting shaft visible in Figure 7, now filled with water and debris, probably was never more than a few feet deep.

The chromite block is made up of large (1 cm ±), dirty gray, intensely fractured chromite grains and fragments interlaced with veinlets of soft, pale green to white talcose material. A narrow zone of disseminated chromite marks the contact (Fig. 8). The host rock is a weathered greenish yellow serpentinized dunite practically free of chromite. It is cut by numerous chalcedony veinlets and slickensided shears. Veins of white to pale green talcose material like that associated with the chromite are abundant in the serpentinite of this area.

In thin section the chromite is opaque except on thin edges where it is deep reddish brown. The grains have been intricately veined by the talcose mineral mentioned above and the sharply angular fragments so produced resemble a breccia.

The talcose mineral could not be definitely identified. It is soft, white to pale green, with a pearly luster on cleavage faces. It is insoluble in boiling concentrated HCl, exfoliates slightly before the blowpipe and assumes a porcelaneous appearance, but is infusible or only slightly fusible. Optically

it is negative, uniaxial or biaxial with a very small optic angle; it has parallel extinction, X is perpendicular to the plates, Np = 1.536, Ng 1.542 (±0.002). It is close to saponite but has lower indices of refraction than those usually reported for that mineral. Thermal analysis curves suggest the presence of both saponite and antigorite, but the sample was too impure to yield trustworthy results.

The fracture pattern in the Ernoule chromite mass is quite similar to that observed in other New Caledonian chromite deposits where the fractures are filled with serpentine. It is not clear whether the talcose mineral is to be ascribed to weathering or to hydrothermal alteration. Evidence would seem to favor weathering, for the prospect is located well inside the borders of the great ultramafic massif which makes up most of the southern quarter of New Caledonia, and there are no younger intrusives or other phenomena suggestive of a hydrothermal origin.

Moi de Mai.—This mine is located 26 kilometers northeast of Noumea in the southern New Caledonian ultramafic massif. It was being reopened at the time of the writer's visit but the underground workings were inaccessible. M. Guepy, engineer in charge, described the ore as occurring in connected tabular bodies (*filons*), vertical and inclined, consisting of lenses of more or less massive chromite, variable in thickness, and bordered by disseminated chromite. The host rock is a grayish olive-green partly serpentinized dunite which near the ore body characteristically contains rounded inclusions of fine grained amphibolite.

A sample of ore from the storage bin is massive, shiny black very pure chromite cut by a gabbro pegmatite dike and by a few veinlets of soft white to pale green serpentine. The chromite crushes to conchoidal flakes which are brownish yellow on thin edges and reddish brown where thicker.

An amphibolite specimen, collected from an 18 in. rounded "boulder" in the dunite within a few feet of the ore body, is a fine, even grained black rock in which the sparkling cleavage of hornblende is quite noticeable. In thin sections the rock consists of an hypautomorphic-granular aggregate of hornblende and colorless serpentine. The hornblende is moderately pleochroic in shades of brownish gray and has a large negative optic angle.

Tontouta Area.—A number of chromite specimens were collected from a dump at the mouth of the Tontouta river. According to M. Maurice Venard, Chief of the Bureau of Mines, New Caledonia, this ore probably came from the Suzanne and General Gallieni mines near the headwaters of the river, approximately 45 kilometers north-northwest of Noumea. Many of the specimens from the dump are *chrome-pique*, with small chromite grains disseminated through yellowish-green serpentine similar to those collected at the La Coulee mine. Fairly massive chromite cut by serpentine-filled fractures is also common, and specimens of "grape ore" and "leopard ore" occur, the chromite forming elliptical masses up to several centimeters in length, scattered through a matrix of greenish yellow to brown weathered serpentinite. In the "grape" and "leopard" ore the longer axes of the elliptical chromite nodules tend to have a parallel orientation. Serpentine-filled cracks cross the

chromite nodules and in some cases there is a suggestion that these nodules have been disrupted to give disseminated chromite.

In thin section the chromite of a specimen of "grape ore" appears as angular to subrounded fragments, the centers of which are deep reddish-brown in transmitted light. Most of the chromite has black borders and is crossed by black-bordered cracks. A pattern of serpentine-filled fractures is likewise present, some having black borders but a majority cutting cleanly through the brown translucent chromite. The groundmass serpentine is pale yellow, somewhat limonite-stained, but free of dusty magnetite. The serpentine has the typical mesh structure and is crossed by chrysotile veinlets parallel to those cutting the chromite.

Tiebaghi Dome.—Near the northern end of New Caledonia an ellipsiodal peridotite mass known as the Tiebaghi dome (Fig. 1) rises some 600 meters above the adjacent Eocene sediments. From this peridotite body has come over one and three quarters million tons of chrome ore, representing perhaps four-fifths of New Caledonia production. Four mines have accounted for almost all of the Tiebaghi dome production, Tiebaghi, Fantoche, Chagrin, and Alpha. Of these the Tiebaghi is the most important and is indeed one of the largest chrome mines in the world, with a total production to date of about one and one half million tons of high grade ore, averaging 55 to 57 percent Cr_2O_3. The Fantoche and Alpha mines have been closed. The writer was able to visit only the Chagrin mine.

Chagrin.—This mine is located on the southeast flank of Tiebaghi dome, about 10 kilometers north of Koumac. Tabular disseminated chromite bodies have been mined, first by open cut and currently from an adit in the serpentinite massif. The chromite is concentrated by tabling after grinding in ball mills. Annual production is of the order of a few thousand tons of concentrate, running about 56 percent Cr_2O_3.

The ore mined by open cut came from a vertical tabular body striking 110° true. It was more than 300 feet long and of variable width, reaching a maximum of about 17 feet. The adit of the operating mine enters the serpentinite hill 50 feet north and about 100 feet above the vertical termination of the open cut ore body. The mine was temporarily closed at the time of the writer's visit; he was informed, however, that the ore body being mined is similar to that exposed in the open cut but is at right angles to it. Specimens collected from a dump at the entrance to the operating mine are much fresher but otherwise identical with those from the open cut.

A sketch of the abandoned working face (Fig. 9) shows the nature of the open cut ore body. It consists of layers of nearly massive to sparsely disseminated chromite alternating with layers and lentils of chromite-free serpentinite. Nearly vertical, lenticular masses of disseminated chromite occur on either side of the main mass. So far as could be determined from the open cut, only the upper termination of the ore body was reached; it extends east, west and downward beyond the limits of the cut. The adit shown on the sketch enters the hill only a short distance and appears to end in ore.

Ore from the open cut is deeply weathered, soft and crumbly and crossed by numerous chalcedony veinlets. The weathered serpentinite is very pale yellowish gray to greenish and brownish yellow and the chromite grains are dull black and intensely fractured. The serpentinite within and immediately adjacent to the disseminated chromite is very pale greenish yellow and bleached in appearance; away from the chromite it grades into darker yellow to yellowish green serpentinite. As seen in thin section, the lighter colored material consists of a mesh of intersecting veinlets of cross-fiber serpentine (chrysotile?) surrounding patches of colorless, nearly isotropic serpentine or chlorite. The darker, yellowish green serpentinite has a similar mesh of chrysotile veinlets, but the veinlets carry abundant magnetite, or, where

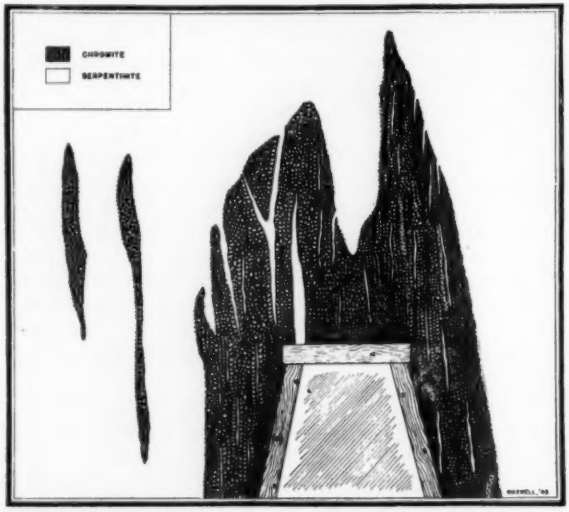

FIG. 9. Sketch of abandoned working face, west end of Chagrin open cut. Base of sketch to top of ore body is about 5 meters.

magnetite is less abundant, the veinlets surround a yellowish green to brownish green pleochroic serpentine with moderate birefringence, resembling bowlingite. The light and dark serpentinites are completely gradational, with the mesh of chrysotile veinlets continuing without interruption from one to the other, and furthermore the darker serpentine locally extends between the marginal chromite grains. It seems probable, therefore, that the light colored serpentinite of the ore body and the dark colored serpentinite of the wall rock were originally a continuous mass of dunite.

The chromite grains vary from about ½ to 3 mm in diameter. They are subhedral to anhedral, considerably rounded and corroded and intensely fractured, the fractures being filled with serpentine. Centers of thinner grains

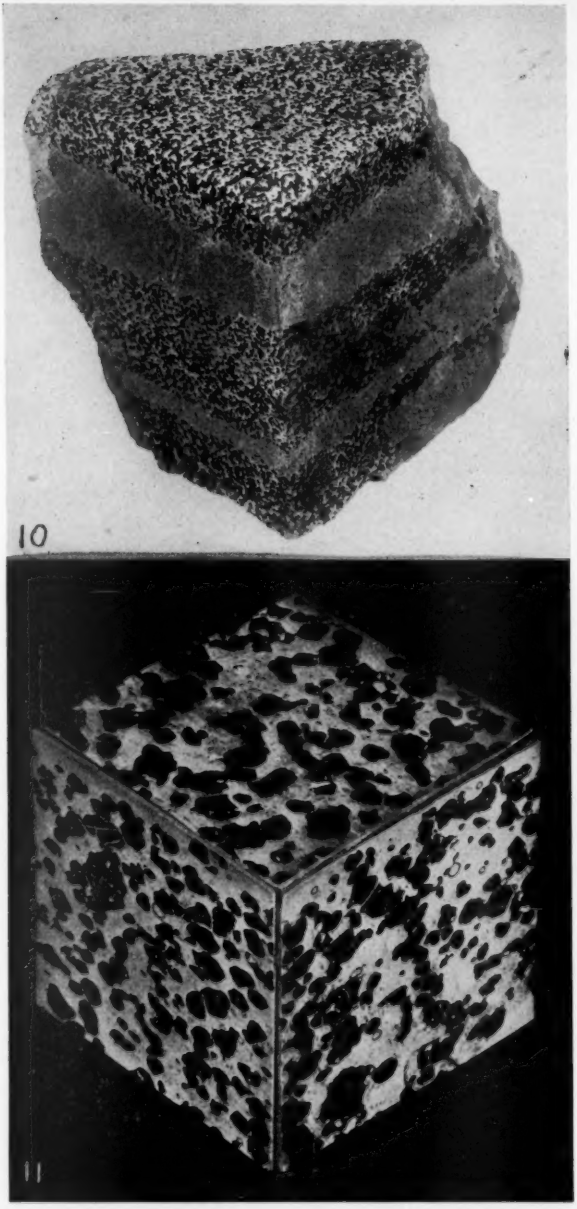

FIG. 10. Banded chromite ore from Chagrin mine. Oriented thin sections were cut parallel to the three mutually perpendicular faces. × 2/3.

FIG. 11. Photomicrographs of thin sections of the banded ore, oriented in the same manner as the ore above (Fig. 10). × 5.

are deep orange brown in transmitted light. The grains have black opaque borders and are crossed by black lines.

Fresh ore from the working mine is quite firm and hard. The accompanying serpentinite is greenish to yellowish gray. Thicker serpentinite layers have much brownish green pleochroic serpentine and are darker in color than serpentinite in the adjacent chromite-bearing layers which contain less of the pleochroic serpentine. The chromite grains are shiny black, corroded and intensely fractured. A few contain minute inclusions of olivine (negative 2V about 85°). Where serpentine-filled cracks have penetrated to these minute inclusions they have been serpentinized. This relationship has been noted elsewhere (12, 13).

In most thin sections serpentine-filled fractures crossing the chromite grains have a sharpness and regularity suggestive of a shear pattern. To evaluate this possibility, oriented thin sections were cut from two specimens of layered ore collected outside the adit of the Chagrin mine. On these two specimens cracks crossing chromite grains form a definite pattern indicating elongation in two directions within the plane of the banding (Figs. 10, 11). Furthermore, serpentine interstitial to chromite grains and in chromite-free bands shows a similar pattern (Fig. 12). Olivine remnants and brownish-yellow serpentine with moderate birefringence are cut by a network of colorless serpentine veinlets in a pattern similar to that formed by the cracks crossing the chromite grains. In many cases the veinlets are continuous from serpentine into chromite grains. Much of the colorless serpentine has a cross-fiber structure suggestive of chrysotile.

Significance of "Bleached" Serpentine.—The close association of chromite with pale yellowish green serpentinite has been noted in the La Coulee and Chagrin deposits and in specimens from the Tontouta ore dump. The yellowish green serpentinite grades rather abruptly into darker green to greenish black serpentinite of the wall rock. In thin section the only apparent difference between the two serpentinites is the abundance of dusty magnetite and/or green to greenish-brown pleochroic serpentine in the dark variety and the absence of scarcity of these in the yellowish green serpentinite.

In the specimens studied, disseminated chromite grains in serpentinite and serpentinized peridotite are black and opaque or very dark brown with black margins and cross-cutting lines. Many also have fringes of opaque, dusty, magnetic particles similar in appearance and grain size to the magnetite granules concentrated along veinlets in serpentinite (Figs. 4, 6). With increase in proportion of chromite to serpentinite the dusty magnetite and pleochroic serpentine become less abundant and the chromite is more translucent and lighter brown in color by transmitted light. It appears that iron has been concentrated in and on the chromite grains, either adhering to the grain margins as magnetite crystals or actually entering the chromite space lattice to form the opaque margins of the grains. The surrounding serpentine is left relatively iron-poor.

In many chromite deposits a sheath of chlorite or kaemmerite surrounds black-bordered chromite grains. According to Lewis, as quoted by Fisher (11) development of the chlorite is attributed to outward migration of alumina

from the chromite. Amin (13) postulates that magnesia also migrates outward to form magnesite and the black border develops as a result of residual enrichment of the chromite in iron oxide. Fisher (11) however, believes the iron oxide was deposited on the chromite grains, rather than being a product of residual concentration. At any rate, there is no evidence for outward migration of alumina or magnesia from chromite grains in the deposits described here, for neither chlorite nor magnesite has formed around the grains.

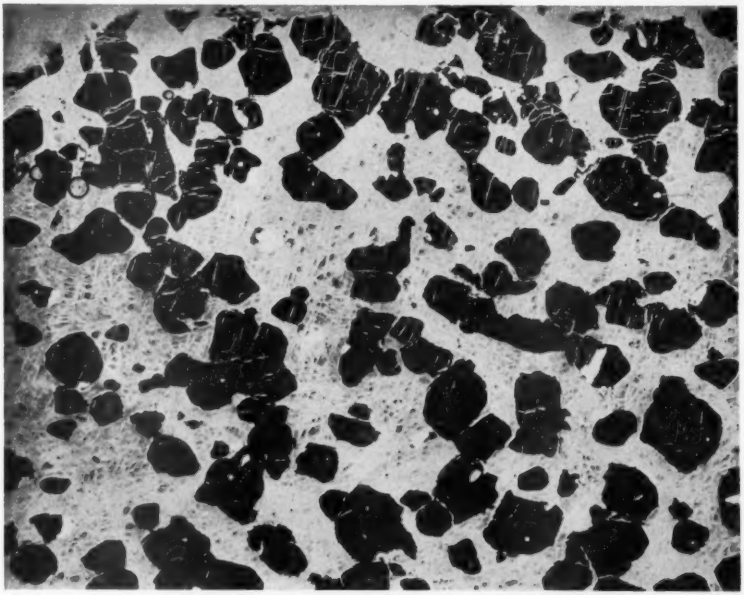

FIG. 12. Same photomicrograph as the top of the block in Figure 11 showing correspondence between the shear pattern in chromite and serpentine. × 9.

Development of magnetite in serpentine derived from olivine occurs at the time of serpentinization. It seems probable that movement of iron oxide resulting in "bleaching" of serpentine adjacent to chromite also takes place in the presence of the serpentinizing solutions. The addition of iron oxide to chromite grains at least post-dates the corrosion of these grains because black margins and "whiskers" of magnetite dust are developed equally on crystal faces and corroded cusps of chromite grains. The process pre-dates weathering; the weathering of serpentine is accompanied by liberation of limonite, which is visible in both hand specimen and thin section. Many specimens of "bleached" serpentinite are completely fresh and contain no

limonite. Where ore bodies are exposed to weathering, as at the Chagrin open cut, the color difference persists in weathered specimens, the "bleached" serpentinite becoming very pale yellow and the wall-rock serpentinite a darker greenish yellow or brownish yellow. Similar zones of yellow to yellowish green serpentinite associated with chromite have been observed rather widely (13, 14, 15), in some cases under conditions where weathering seems to be ruled out as a possible explanation.[4]

Where iron oxide is taken up by chromite from nearby serpentinite, as postulated above, one would expect disseminated chromite grains and margins of more massive deposits to be higher in iron (and presumably lower in chrome) than the centers of the deposits. Such a relationship is occasionally noted (16). According to Tester [5] peripheral zones at the Tiebaghi mine run lower in Cr_2O_3 than the center of the deposit, and disseminated chromite, reconcentrated in sands, contains more iron than the lode deposits. Blanchard (10) gives two partial analyses of Tiebaghi ore, one of nodular chromite disseminated in a serpentine matrix, the other of massive chromite. Assuming all the iron of the analyses is associated with the chromite, the chrome-iron ratio of the massive and nodular ores are respectively 4.2 and 3.2.

Stephenson (17) measured the magnetic permeability of a number of specimens of chromite from Casper Mountain, Wyoming. He found that density, opacity, and magnetic permeability increased with increasing iron content, those with the largest amount of iron ($Fe_2O_3 = 53.0$, $FeO = 27.4$, $Cr_2O_3 = 13.7$) being dense, black, opaque and nearly as magnetic as magnetite. On the other hand samples lower in iron were progressively less dense, of lighter color in transmitted light, and less magnetic, the least magnetic sample containing 18.22% Fe_2O_3, 18.05% FeO, 44.74% Cr_2O_3. Dresser (18) in studying chromite from Black Lake, Quebec, found that the black, opaque margins and veinlets of chromite grains were higher in iron and more magnetic than the reddish brown, translucent centers of the grains. Singewald (19) showed that the magnetic portions of two Maryland chromite sands contained considerably more iron than the non-magnetic portions. There does, therefore, seem to be a general tendency for iron-rich chromite in a given deposit to be relatively more magnetic and less translucent than associated chromite carrying less iron, though there is abundant evidence that the relationship is not a simple one.

A number of specimens of New Caledonian chromite were tested for magnetism by a simple but rather sensitive method. Powdered chromite mounted in oil on a glass slide under a cover glass was observed with medium power magnification while a strong hand magnet was passed back and forth nearby. Many of the partly or wholly opaque fragments rotated to align themselves with the changing magnetic field but the lighter brown, more transparent fragments were unaffected. Fourteen specimens of chromite disseminated in serpentinite and 9 specimens of relatively massive chromite with little associated serpentine were examined. All of the disseminated

[4] For example, in the Wood Mine, Pennsylvania, at depths below weathering, more than 500 feet below the surface. E. Sampson, personal communication.

[5] Allen C. Tester, personal communication.

chromite was at least slightly magnetic, much of it strongly so. Three of the more massive chromites were non-magnetic, three contained a trace of magnetic material and the other three contained about as much magnetic material as the least magnetic of the disseminated chromites. The comparison of specimens from the small chromite "dike" at La Coulee (Fig. 5) proved to be particularly interesting. Two specimens of disseminated chromite from the dike margins were strongly magnetic; of three specimens from the more massive interior, two were non-magnetic and one was slightly magnetic. The results suggest that selective magnetic separation would be useful in beneficiating some disseminated chromite ores and sands.

Origin of the Chromite Deposits.—A study of the La Coulee, Chagrin and Ernoule ore bodies, of thin sections of these ores and of specimens from the Tontouta dump reveals certain features suggestive of the mode of origin of these deposits.

1. Chromite is present in tabular masses, steeply dipping to vertical, consisting of disseminated chromite grains in serpentinite, with or without associated blocks and sack-form bodies of massive chromite. Much of the disseminated ore is roughly layered, the chromite alternating with layers of chromite-free serpentinite. Where disseminated ore contains masses of chromite these tend to be oriented with their largest dimension in the plane of the layering.

2. The chromite is intermixed with and surrounded by a thin margin of yellowish green "bleached" serpentinite. The contact between "bleached" and "unbleached" (greenish black) serpentinite is indistinct, with minute tongues of the dark serpentinite projecting between marginal chromite grains. "Bleached" and "unbleached" serpentinite are similar except that dusty magnetite and brownish green, pleochroic serpentine are characteristic of the "unbleached" and practically absent from the "bleached" serpentinite. This relationship holds for serpentinite lenses within the disseminated chromite ore bodies as well as for the contact of the ore bodies with wall rock.

Chromite disseminated in serpentinite tends to be nearly opaque; it commonly has black margins and is crossed by black-bordered cracks. Many such grains have fringes of magnetic dusty black opaque material, presumably magnetite. The more massive chromite, away from serpentine, is much more uniform and is lighter in color by transmitted light. The black margins and opaque grains have been noted frequently, and have been ascribed to enrichment of the chromite in iron or to the formation of magnetite. Some such process seems to have operated in the New Caledonian chromite. Chrysotile veinlets in the dark serpentinite of the wall rock almost all have stringers of dusty magnetite in their centers. Where such veinlets cross into a disseminated chromite body the magnetite is absent, and the chromite grains tend to be black and opaque.

3. There is no evidence of a discontinuity, such as an intrusive contact or vein wall, at the margins of the tabular chromite bodies. Prior to serpentinization the dunite apparently was continuous from wall rock into the ore body. Lenses of serpentinized dunite within the ore bodies are indistinguishable from wall rock.

4. A pattern of serpentine-filled fractures is present in most chromite specimens examined. The fractures are quite regular and cut across chromite grains and interstitial serpentine alike. In two specimens of banded ore examined the fractures seem to indicate elongation in two directions at right angles to each other within the plane of the vein. A similar pattern of chrysotile veinlets is present in partly serpentinized dunite collected at a distance from known chromite deposits.

5. The chromite grains commonly carry minute inclusions of olivine; these are serpentinized where reached by serpentine-filled fractures. Some of the olivine crystallized before or contemporaneously with the chromite. Much of the chromite has been broken and corroded by silicate minerals suggesting the chromite had finished crystallizing before the dunite matrix became solid. The chromite is fractured, even the smallest grains. This suggests that fracturing occurred prior to serpentinization when the chromite grains were in contact with olivine crystals, otherwise the smaller grains should have been protected from fracturing by the relatively plastic serpentine. These observations agree with Fisher's conclusions after studying specimens of New Caledonia chromite (11).

6. Pyroxenite and gabbro pegmatite dikes cut the ore bodies and country rock. These dikes seem to have been emplaced prior to serpentinization, for pyroxene has been converted to bastite near the serpentinite wall rock and along cross-cutting fractures.

7. The curved slickensided fractures common to serpentinites are also prevalent in New Caledonia. Such fractures cross the country rock and ore bodies alike with no evident relationship to the serpentine-filled fractures noted above or to the banding in the ore bodies.

In the writer's opinion the above observations are best explained by assuming that the chromite crystallized at depth, presumably by crystal settling. It was carried upward as blocks, fragments and disseminated crystals during the emplacement of the ultramafic host rock, in the manner suggested by Thayer (20) and others. As the ultramafic mass became more rigid the last movements produced the fracture pattern in ore body and country rock. Gabbro and pyroxenite pegmatite dikes were emplaced at about this stage. Serpentinization accompanied or followed late stage fracturing and the fractures were filled with serpentine, largely cross-fiber chrysotile. During serpentinization the solutions involved brought about the migration of iron from the serpentinized olivine to the surfaces of the chromite grains. Later regional deformation produced curved slickensided fractures in the serpentinite and peridotite.

Numerous arguments can be advanced against the simplified interpretation given above. The chromite "dikes" at La Coulee and the intersecting "filons" said to characterize the Moi de Mai deposit could be cited as evidence of movement of the chromite as a fluid, either as a melt or in hydrothermal solutions. The Fantoche deposit has been interpreted as a vein.[6] Serpen-

[6] Blanchard (10) quotes Sinclair as saying ". . . at the Fantoche mine the vein formation is clearly later than that of the host rock, evidenced by wall rock alteration of the chromite-serpentine contacts, together with instances of the ore grading into unmineralized serpentine."

tinization and the formation of the serpentine-filled shear fractures in host rock and ore might be ascribed to solutions derived from later intrusives percolating through previously sheared ultramafic rock.

On the basis of the writer's field work none of these arguments can be definitely refuted. It does seem unlikely, however, that the serpentinizing solutions could have originated elsewhere than within the ultramafic rocks themselves. The ultramafics comprise such a huge mass of material, the whole permeated by the serpentinizing solutions to a greater or less extent, while later feldspathic intrusive rocks are widely scattered and almost insignificant in volume. The norite mass near Plum, while of considerable size, was intruded after the serpentinization.

If the serpentine-filled fracture pattern is to be ascribed to stresses resulting from emplacement of the ultramafic rocks, then a systematic study of the pattern should show some relationship to the outlines of the masses. In this connection careful compilation of data on the attitude of tabular chromite occurrences and of compositional banding within the ultramafics would also be highly desirable. The information available to the writer, partly acquired in field work, partly taken from Glasser (*7*), is shown in Figure 1.

ACKNOWLEDGMENTS.

I am indebted to A. C. Tester, D. F. Frasche, Edward Sampson, H. H. Hess and G. B. Leech for criticizing the manuscript, and to Professor Tester and Mr. Frasche for additional information on New Caledonian geology and chromite deposits. F. L. Ferris, Jr., prepared the line drawings; the photomicrographs were taken by Fred Anderegg and Willard Starks.

E. J. LeBreton, A. N. Spence and many other friends in the armed services contributed greatly to these studies by providing transportation, equipment and companionship for the numerous field trips.

PRINCETON UNIVERSITY,
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April 1, 1949.

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MINING GEOLOGY AND THE ENGINEERING ASPECTS OF MINERAL EXPLORATION.[1]

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ABSTRACT.

The practice of Mining Geology is essentially an engineering enterprise directed to the discovery, exploration and development of mineral deposits. It was so recognized many years ago and has been pursued as such an activity by numerous geologists for over fifty years. However, the the past and present-day geological fraternity, as a whole, has been loath to recognize the inseparable relationship of mining geology and engineering.

The comprehensive exploration and discovery of mineral bodies, which by definition is mining geology, is based equally upon: (a) basic training in the sciences of physics, chemistry, mineralogy, and geology and special knowledge in economic and structural geology; (b) fundamental training in the engineering sciences of mathematics, mechanics, surveying, mining, and mineral dressing.

Inasmuch as mining geology is a phase of engineering and has been so described and practiced for many years, the writer recommends that geologists, as a whole, no longer neglect to take action to establish mining geology in its true role as an engineering endeavor.

ANY analysis of the engineering aspects of exploration for mineral deposits must include some consideration of the processes of mining geology since mining geology and mineral exploration are inseparably related as engineering enterprises. Under most circumstances the terms can be and should be used to designate a similar practice. Perhaps as the result of this discussion some points at issue, and considered by many to be in conflict, will be reconciled. It is hoped that this paper will act as a spur to bring into effect a unified movement that will have the purpose of defining and fixing the several scientific and engineering areas of geology.

Mining geologists have been practicing engineering in the exploration for mineral deposits for over fifty years in much the same manner as they do today. Sales (1),[2] Linforth (2), Peele (3), Lawrence (4), Lindgren (5, 6), Brock (7), and many others found occasion several years ago to write specifically concerning the fundamental relationship that exists between such fields of work. However, it seems that the past and present-day geological fraternity, as a whole, has been continually loath to recognize the fact. Indeed, one is led to the conclusion that some geologists consider it beneath their dignity to be associated with an engineer let alone to be known as one. It is unfortunate that this viewpoint has developed. Some excellent analyses and concepts of geology and the geological profession were offered recently during

[1] Presented before the Society of Economic Geologists, San Francisco meeting, February, 1949.

[2] Numbers in parentheses refer to Bibliography at end of paper.

the "Training in Geology" symposia (8) and other conferences (9). Likewise, it is true that some warped viewpoints regarding engineers were also propounded during the discussions. We geologists need to realize that an engineer is in some cases a geologist, and that a geologist may be an engineer. We can no longer neglect to crystallize our thinking and define our subject matter and thus make rational analyses in keeping with the facts—employing in the process the analytical method of the engineer.

The full, efficient exploitation of any mineral mass is dependent on two more or less interrelated but nonetheless distinct functions. They are, namely: (a) The exploratory search, discovery, and development work necessary to demonstrate the presence of ore for mining. This phase of work can be done efficiently only by unraveling and interpreting the geologic setting that controls the localization of the sought-for mineral substance; (b) The mining or producing of the discovered and developed ore by using man-power and machinery in a controlled, planned method. Taking the elements of the title of this paper for analysis and being concerned directly, therefore, with the first of the above-named functions, yields the following:

1. Mineral exploration is the search for hitherto unknown or unrevealed mineral deposits in or on the earth's crust. The basic, fundamental influence leading to such exploration is that of a desire for economic gain and of securing mineral materials for use.

2. Engineering is defined as the art and science by which the properties of matter and sources of power in nature are made useful to man.

3. Science is knowledge reduced to law and embodied in system—it is expertness, or ability to do, resulting from knowledge.

4. Mining geology is an area of the science of geology, as a whole, by which mineral deposits are discovered and explored for economic gain. Specifically, it is a special sphere of economic and structural geology.

From the above definitions it follows, without qualification, that the science of mining geology, as it is applied in exploring for economic mineral bodies, is engineering. This is not a new concept; it was recognized and described over thirty years ago and it has been further discussed more recently at some length by Schmitt (10), McKinstry (11), Clark (12), and others. For some reason, however, the relationship of mining geology and engineering has never fully crystallized to a stage where definite, concerted action has been developed to establish mining geology in its proper professional role as an engineering endeavor.

The comprehensive exploration and discovery of mineral bodies, which by definition is a phase of mining geology, is based equally upon:

1. A scientific knowledge of the natural laws that may have controlled the mode of occurrence of any given mass as to its trend, attitude, continuity, size, shape, and mineral character. This is the scientific aspect of mining geology and, to be applied successfully, requires (a) fundamental knowledge of chemistry, physics, mineralogy, and geology in general, and (b) special training in economic and structural geology, geophysics, and geochemistry.

2. An ability and training in engineering practice of such a scope as to accomplish satisfactorily—(a) the survey and engineering record of the existence of all controlling elements that may be directly observed or secondarily revealed by one or more of such means as drill-hole probing or geophysical testing; (b) the guidance in the selection and use of machinery and equipment that may be required for probing and testing the mineralogical and structural character of the mineral mass; (c) the interpretation of geologic relationships (structural, economic, and mineralogic) of the body both as to their individual and cumulative effects by the use of descriptive geometry, mathematics, physics, chemistry, or mechanics; (d) the determination of the measurable and potential quantity and tenor of the sought-for material in a given mineral mass by applying a knowledge of geologic science, mathematical procedures, mining practices, and beneficiation methods; (e) a contribution to the adoption of a planned method for mining and developing the given mineral body. Such are the engineering aspects of mining geology. It is evident that they require a basic or special training in several engineering science areas for their proper, full pursuit.

3. A facility in the art of expression and of draughtmanship in order to convey properly—(a) oral and written descriptions and conclusions of the exploration practices used, and of their results as they have been applied in analyzing a mineral occurrence; (b) diagrams and maps of such detail and clarity as to be of ready interpretation and usefulness for conveying pictorially pertinent conditions governing the exploration analysis. These arts are neither peculiarly scientific nor engineering in nature but they are, nonetheless, essential to the complete success of the geologist's professional enterprise.

From the above it becomes apparent that mining geology is a specific, differentiated area of engineering built upon a knowledge of certain basic and special sciences. It is neither economic geology nor structural geology when these terms are used to define scientific practices which do not pertain specifically to a gainful, ore-finding process. It is not mining engineering when the term is employed with reference to an activity fundamentally devoted to production and delivery of mineral material from the earth's crust. The mining geologist is concerned with engineering production practices and with geologic science insofar as such elements have a bearing on the discovery of sought-for mineral bodies. Just as it is not possible to make a versatile mining geologist from a mining engineer who knows mining methods but little economic and structural geology, so too it is impossible to accredit an economic geologist as a mining geologist and engineer if he does not have a rounded concept of mining practices, mineral dressing, surveying, descriptive geometry, mechanics, and mathematics. All of the academic, pure scientific training that can be conceived in petrography, petrology, principles of ore deposition, metamorphism, and structural geology will not wholly fit the man as the exploration engineer he must be to serve as a mining geologist. A condition arose during the early part of World War II which will serve as a confirming illusrtation of this statement.

Many of us will recall that the search for new mineral supplies in the United States often seemed to be confounded, more or less, by the overlap of activities pursued simultaneously on a given deposit by geologists of the U. S. Geological Survey and engineers of the U. S. Bureau of Mines. Duplication of effort frequently ensued, which sometimes resulted in disharmony and misunderstanding in addition to a waste of money and man-power. In many cases the geologist didn't have a sufficient grasp of engineering-exploration principles to proceed logically; in other instances, generally less numerous it seems, the mining engineer was lacking in a necessary background knowledge of economic and structural geology. In the writer's opinion much of the confusion might have been allayed if spheres of responsibility had been previously defined and fixed on the basis of sound, reasonable concepts of what training requirements are necessary for mineral exploration.

The question may be put: "This is all very well but what can be done about it?" The solution basically is no more difficult than that of the problem which has been met by the chemists and chemical engineers, by the metallurgists and metallurgical engineers, and by the ceramists and ceramic engineers. The distinction of professional areas in these fields is widely recognized and is accomplished without sacrifice of the prestige of any division. Therefore, certainly there is ample precedent to make a valid claim if we must justify a premise that the sphere of responsibility of the mining geological engineer should be defined as separate from that of the geologist working in pure science. The answer to the question of what is to be done rests alone on us, individually and collectively, as members of the whole geological profession. No other group will carry, or should be expected to carry, the problem to final solution—and solve it we must if we are ever to gain proper, complete professional recognition. A fully established professional standing as scientists and engineers is our due, just as much as is the requirement we have of guiding our concept of the situation to acceptance and approval by all concerned. What of an engineering profession that is so ill defined as to have attained recognition as an accredited professional curriculum in only 7 colleges or universities in the United States[3] when, with the bame basic opportunity, chemical engineering and metallurgical engineering each have established such stature as to be accredited in no less than 54 and 35 cases, respectively? Can we rationalize a situation like this? Can we afford to ignore it and, in so doing, permit the engineering phase of our profession to be looked upon as somewhat of a professional freak or educational mistake?

Two of the most frequently recurring comments made during the "Training in Geology" conferences were: (a) That young people are not being attracted to geology and, therefore, strong, new blood necessary to maintain a growth of the profession is not entering our educational channels for geological training and (b) that geology, as a whole, seems to be continually and progressively losing ground to other sciences. It was indicated that we have lost the atmosphere, have all but given up the hydrosphere, and that we are rapidly losing such elements as the geophysics and geochemistry of the lithosphere.

[3] It is recognized, of course, that some universities teach mining geology under the name of economic geology.

Indeed, it has been indicated in this paper how a tendency has existed, more or less, for taking mineral land exploration and evaluation into another professional area. In the writer's considered opinion, these are neither abnormal nor completely unreasonable trends under the circumstances that presently obtain. For example, how can geology, which within itself is certainly most romantic, be "sold" by us as salesmen-scientists to younger people when we, as a group, apparently are without clear-cut, crystallized concepts of all of its aspects? Further, how can we fail to lose influence and control in the field of earth-science study without having established a well-defined understanding of the broad scope of all possible areas of interest?

The next question to arise is: "How are we to accomplish such training as seems necessary to fit properly a mining geologist for the engineering-scientific duties and responsibilities he must assume?" Again, the solution is fundamentally no more difficult than that of the problem which confronts several other engineering-science professions that have become recognized in their true light and full scope.

One writer (13) has suggested, somewhat facetiously, perhaps, in fixing his point, that, with suitable raw material, satisfactory training in mining geology can be accomplished through a period of 16 years. Even though we concede that a training period of such duration may be most desirable it is apparent that it is certainly not feasible under the system followed today in most colleges and universities. This is not the place to enter a discussion of curricula; suffice it to say, however, that it basically is no more difficult to train a mining geologist as an embryo engineer-scientist in four or five years than it is to train any other kind of engineer. Though longer academic training periods may be desirable they must not be considered as absolutely essential to our successful planning and accomplishment of purpose if we are to compete on equal grounds with other professional engineering and scientific fields. Granting, in all cases, the more extensive the academic training the more versatile the man, other factors being equal, we are faced nevertheless with a situation wherein we must develop courses of study which will permit us to turn out a reasonably suitable product within the nominal number of years of most college cycles. Just as some of us heretofore learned our engineering as undergraduates and then received most of our geological training in graduate school, many men trained as mining engineers have been forced to acquire in industry the necessary special training as exploration engineers. Neither of the above methods of securing training are, or should be considered, necessary for the development of a mining geologist. In the first place, it is not feasible on a competitive basis with other engineering professions for us to require post-graduate academic training in every case and, secondly under the conditions of the latter method mentioned, well-rounded versatile knowledge may be lacking. The man may function excellently when his activities are confined in a local area but he may be hampered when approaching more widely diversified field problems. The benefits of experience in industry cannot be discounted but they should be looked upon as supplementary to scientific, technical training. In fact, industrial experience is essential before most men are qualified to serve satisfactorily in mineral exploration. This condi-

tion is not unique to mining geology, of course, as it is equally true of the development necessary in other engineering professions.

In summary, it is apparent that mining geology is engineering and is the professional sphere of mineral exploration. This concept was defined over thirty years ago by Lawrence, Lindgren, Brock, and others; it was being taught by Kemp fifty years ago and was being brought into practice by Winchell and Sales at the turn of the century.

With all respect to the great accomplishments wrought by many individual mining geologists, it seems that geologists, as a whole, today still stand at the cross-roads, undecided as to where the future of the profession lies. Some men, it is true, have become aware of the need to re-examine and re-evaluate the whole scheme of the earth sciences and several conferences reaching for a solution have been held in recent years. However, simply to confer is not enough and the time has come, in fact is overdue, when we as educators and as industrialists must take specific action to design and support a process whereby a mining geologist may acquire essential training and win full professional recognition as an engineer and as a scientist. The problem is not insoluble.

MISSOURI SCHOOL OF MINES AND METALLURGY,
ROLLA, MISSOURI,
March 11, 1949.

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DISCUSSION AND COMMUNICATIONS

TRANSPORT AND DEPOSITION OF THE NON-SULPHIDE VEIN MINERALS. III. PHASE RELATIONS AT THE PEGMATITIC STAGE.

Sir: From a physico-chemical point of view the paper by Gordon Smith which appeared in the November 1948 issue of this journal is interesting because it informs us about a certain complex hydrous silicate-phosphate-borate system.

The petrological conclusions drawn from the experiments, however, invite further discussion. The present writer will only make some remarks on the general conclusion that one of the two immiscible liquids of Gordon Smith is the mother liquor of pegmatites; the other, of ore veins.

Fluids supposedly responsible for formation of pegmatites, ore veins, some sort of metasomatism etc. occupy a rather unique position in our geological picture in that most of these fluids manifest themselves only indirectly by precipitation and dissolution of rock making minerals. These fluids have never positively been observed or sampled after their escape from the place where they formed the "hydrothermal" rock in question. Thus the composition of such fluids can only be calculated indirectly. It should be rather obvious that one of the crucial properties to be required of these vague fluids be that they are able to precipitate the very mineral species of the rock which the fluids are suspected to form.

Gordon Smith records only one rock making mineral (orthoclase) as forming from his fluids. Moreover, this mineral is only found in one of the six runs in which the other solids are not determined. Although it is interesting to know that orthoclase can crystallize from the system investigated by Gordon Smith, no conclusion whatsoever can be drawn as to the implication of the fluids in question in the formation of pegmatites before the undetermined solids are diagnostized. This is particularly true since the composition of the investigated fluids is of an unique composition whose identity to any natural pegmatite forming fluid should be questioned.

HANS RAMBERG.

UNIVERSITY OF CHICAGO,
CHICAGO, ILL.,
Feb. 3, 1949.

USE OF SKETCHMASTER IN COMPILATION OF GEOLOGIC MAPS FROM AIR-PHOTO ENLARGEMENTS.[1]

Sir: This note describes a method of compiling geologic maps, with the aid of a vertical sketchmaster, from data obtained by mapping geology on

[1] Published by permission of the Director, U. S. Geological Survey.

aerial photographs. A sketchmaster [2] is a camera-lucida device designed primarily for use in transferring detail from aerial photographs to a base map. The instrument can be adjusted for scale and corrected for tilt in aerial photographs by raising or lowering the frame on three legs. Lenses that are inserted directly below the semi-transparent mirror can change the scale from 1½ times enlargement to 2 times reduction. Although designed for use by photogrammetrists, this instrument has become useful to geologists in compiling geologic maps. The sketchmaster was developed in 1943, and to date its use has not been described in the geologic literature.

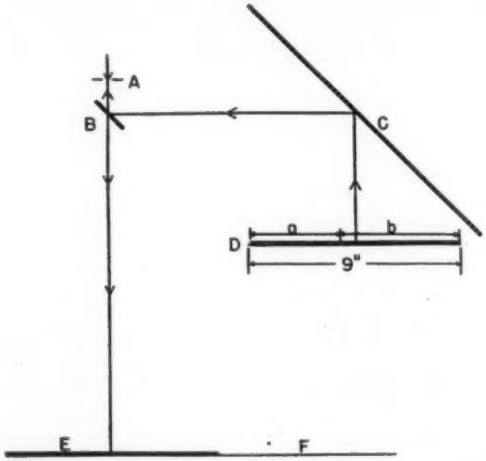

FIG. 1. Schematic diagram of vertical sketchmaster: A, eyepiece; B, semi-transparent mirror; C, rectifying mirror; D, frame for photograph that limits width of print to 9 inches; a, b, two adjacent strips of large photograph; E, virtual image of photograph superimposed on image of base map; F, base map.

By means of a semitransparent mirror in the eyepiece the image of the photograph is superimposed on the image of the map (Fig. 1). A second mirror (C) makes the image that is being transferred appear in an upright position (E).

The sketchmaster has an advantage over other photogrammetric methods

[2] Designed and patented by J. L. Buckmaster, U. S. Geological Survey. Sold by Aero Service Corp., 236 East Cortland St., Philadelphia, Pa.; by Harrison C. Ryker, Inc., 1000 Ashby Ave., Berkeley 2, Calif.; and by Abrams Instrument Corp., Lansing, Mich.

Anonymous, Construction and operation of the vertical sketchmaster, Aero Service Press, 8 pp., privately printed, no date [1943].

Anonymous, Aerial photography. U. S. War Department Technical Manual 5–240, p. 56, 1944.

Anonymous, Reconnaissance mapping with trimetrogon photography. U. S. Army Chart Service, pp. 96–107, 1943.

of transfer (pp. 609–614) [3] because the operator does not require special training, and because it is portable and therefore usable in both office and semipermanent field camps.

With the use of this instrument adequate geologic maps can be compiled on topographic or planimetric bases, provided sufficient horizontal control is available to tie the photographs to the maps.

Available sketchmasters are designed to take a 9″ × 9″ photograph, and most of the contact prints available in the United States are of this size. The design of the instrument limits the width of the photograph accommodated to 9″ (Fig. 1, D); the length in the direction perpendicular to the line between the two mirrors is not limited. If mapping is done on larger photographs, it is necessary to cut or fold the photographs so that they fit into the frame. One successful method of adapting larger photographs for use in a sketchmaster follows:

Each large photograph is cut into three or more parallel strips so that the sum of the widths of any two strips is less than 9 inches. It is then possible to insert into the frame of the sketchmaster two adjacent strips (Fig. 1 a, b). The reason for cutting into three or more strips is that the center strip of any unit of three can be used as the overlapping part for control in adjusting the image of the photograph for scale and tilt.

Illumination is obtained from two lamps, so placed as to give the best ratio of illumination between the photograph and the map. The combined images of the photograph and the base may at times become confusing to the operator, and it may be especially difficult to determine whether a certain line is on the photograph or on the base map. This difficulty can be eliminated by placing a piece of white paper on the base map so that the image of the photograph appears on a white background. When the paper is removed the image of the photograph can be seen more clearly superimposed on the base map. An additional copy of the base map is convenient for distinguishing culture and drainage, and for interpreting the combined images.

I. G. Sohn.

U. S. Geological Survey,
Washington, D. C.,
March 29, 1949.

[3] Smith, H. T. U., and others, Symposium of information relative to uses of aerial photographs by geologists: Photogrammetric Engineering, vol. 13, no. 4, pp. 531–628, December 1947.

REVIEWS

Ore Genesis: A Metallurgical Interpretation. By John S. Brown. Pp. 204; figs. 4. The Hopewell Press, Hopewell, N. J. Price, $3.50.

The author proposes a two-part hypothesis to explain the formation of the hydrothermal ore deposits and to answer some of the objections encountered by the hydrothermal theory. The first step in the assumed mechanism is a gravity separation of immiscible liquid layers like the separation that goes on in a blast furnace (hence the sub-title). This gravity separation is assumed to take place during the cooling of an originally molten earth, by a process by which certain layers of the earth become solid before other layers and so serve as floors on which the heavier constituents of the superjacent layers can accumulate. Above a floor the immiscible layers will of course be arranged in order of their specific gravity. The author believes that the top of a peridotite substratum at a depth of about 60 kilometers froze before the overlying basaltic and granitic substrata and so served as a floor on which were accumulated the immiscible heavy constituents of the basaltic and granitic substrata. These immiscible layers are called magmas, and their positions in order from shallower to deeper zones, in accordance with their specific gravities, would be a pegmatitic magma (with tin and tungsten), several iron magmas, made up of oxides and silicates, and a sulphide magma, itself broken up into a matte layer, a speiss layer, and a lead sulphide layer. The precious metals, always in small amount, would be contained in the lead sulphide layer because in small amounts they are miscible with it. Not all the layers need be present in any given section, but it is possible that some layers are continuous over nearly earth-wide areas.

The second part of the hypothesis assumes that the constituents from these various layers are able to escape upward whenever the superjacent material becomes crystalline and fractures can penetrate to them. The author believes that the constituents move as gases of the simple mineral substances. Magmatic water is held to be an unimportant constituent. Since cooling and fracturing must progress downward from the earth's surface, the shallower layers will be tapped first, and in fact if liquid they must be disposed of before fracturing can penetrate deeper. The distance to which the different gases travel before deposition is determined by their volatilities.

This two-fold hypothesis of stratification by gravity and transport to different distances by degree of volatility explains, in the author's belief, some of the otherwise unexplained relationships which plague us in the study of ore deposition. Few ore geologists will disagree with the author's contention that there is to-day no adequate explanation of the normal succession of deposition of the ore minerals, and increasing numbers of geologists are showing dissatisfaction with the current explanations of zoning in ore deposits. If any hypothesis makes an effort to explain these relationships, it deserves some consideration. To be sure, the ideas are not wholly new, but the presentation is timely. The book suffers greatly from carelessness in writing, editing, and printing. The best part is the 6-page Preface and the figure on p. 139. This reviewer was unable to see why the substance of the book

could not have been presented much more clearly in the length of a typical technical article.

JAMES A. NOBLE.

CALIFORNIA INSTITUTE OF TECHNOLOGY,
PASADENA, CALIF.,
July 5, 1949.

Geologia della Miniera di Montevecchio. By ANTONIO CAVINATO AND PIERO ZUFFARDI. Pp. 40; 1 map in color; figs. 19, many in colors. Bertieri, Milano.

The Montevecchio mine, in Sardinia, which the authors call "a real museum of rocks," contains primarily galena and blende, with subordinate quantities of argentite, chalcopyrite, pyrite, anglesite, cerussite, pyromorphite, bornite, arsenopyrite, pyrrhotite, tetrahedrite, and bournonite. The common gangue minerals, in order of quantity are quartz, barite, siderite, calcite, and fluorite.

As a conclusion to the last chapter, which deals with the mineralization processes, the authors offer a "new suggestion": That it is necessary to distinguish alteration and oxidation effected by descending atmospheric agents from alteration and oxidation caused by ascending hydrothermal solutions. For example, Lindgren and others described zones of oxidation in sulphide deposits when, in the opinion of the authors, their origin should be attributed to surficial alteration. Many of the phenomena of oxidation described up to now, according to the authors, must be regarded not as a particular aspect of the more general phenomena of surficial alteration, but rather as a particular aspect of the more widespread phenomenon of hydrothermal metasomatic processes in minerals and rocks, in which the nature of the carrier and the chemical processes of the transformations that have been produced will have to be better defined. However, convincing evidence to support this unusual conclusion appears to be lacking.

M. L. MIGNONE.

The Ellenburger Group of Central Texas. By PRESTON E. CLOUD, JR., AND VIRGIL E. BARNES. Pp. 473; figs. 8; pls. 45; tbls. 3. University of Texas Publication No. 4621, June 1946. Austin, 1948.

This very ambitious undertaking is something of which the Bureau of Economic Geology of Texas can well be proud. It deals with a great series of Lower Ordovician carbonate rocks of which the limestone are thought to have originated as chemically precipitated carbonate muds, under conditions similar to those found today in the Bahama bank. Broad and detailed stratigraphy is given. There are 27 excellent collotype plates and 16 large charts and geologic maps in an accompanying folder. This volume maintains and exceeds the high standards of previous publications of the Bureau.

Emanuel Kayser's Abriss der Geologie. Part II, Historical Geology. By ROLAND BRINKMANN. Pp. 355; figs. 64; pls. 58. Ferdinand Enke Verlag, Stuttgart, 1948. Price, bound, DM 27.–.

Professor Brinkmann has undertaken an entire revision of Kayser's well-known volume and it is essentially a new text, one of several new ones to appear from Germany within the last year.

Following an introductory chapter, there are thirteen chapters in which is taken up era by era, starting with the Archean and Algonquian, the history and life on the earth, and which for the most part deals with fossils. Plates illustrate the

fossil life and paleogeographic maps illustrate the extent of the sediments. There is also a folded insert giving comparative sections for each era of the different parts of Europe.

The book is sparsely illustrated. The fossil drawings are good but the poor paper poorly reproduces the few photographs, most of which have not been well chosen.

College Geography, 3rd Edition. By EARL C. CHASE AND DANIEL R. BERGSMARK. Pp. 790; figs. 295. John Wiley and Sons, New York, 1949. Price, $5.00.

This well-known geography has been rewritten to reweigh the subject matter in the light of events since 1940. Considerable data have been added about Russia, particularly regarding its fuels and iron ore resources.

Part I deals with World Environment; Part II with Climatic Regions and Human Activities. Part III is concerned with Minerals and Mineral Industries; Part IV deals with Trade and Transportation. Part III deals with the occurrence, distribution, and industries of iron and steel in different parts of the world, and similarly with the mineral fuels, water power, base metals, and building materials.

The book is comprehensive, well balanced and very readable.

BOOKS RECEIVED.

M. L. MIGNONE.

U. S. Bureau of Mines—Washington, D. C., April 1949.

R. I. 4418. Investigation of Potato Mountain Tin Placer Deposits, Seward Peninsula, Northwestern Alaska. HAROLD E. HEIDE AND F. A. RUTLEDGE. Pp. 21; figs. 7; tbls. 10. *256 drill holes yielded concentrates averaging 35.35 to 67.57% Sn mostly in slightly rounded cassiterite grains with some nuggets.*

R. I. 4431. Investigation of Copper-Nickel Deposits of the Stillwater Complex, Stillwater and Sweetgrass Counties, Mont. ROBERT N. ROBY. Pp. 10; figs. 7; tbls. 2. *Copper-nickel sulfides in pods and lenses in norite and hornfels; low grade; nickel content averages 0.42%, copper 0.37%; sulfide minerals are pyrrhotite, chalcopyrite and pentlandite.*

R. I. 4436. Investigations of Boiling Springs Manganese-Iron Deposits, Cumberland County, Pa. S. E. BURTON AND ROBERT S. SANFORD. Pp. 20; figs. 5; tbls. 8; churn drill holes. *Lower Paleozoic quartzites and limestones partly overlie Precambrian crystalline rocks of igneous origin; final product contained 53.3% Mn, 7.6% Fe, 13.5% insoluble and 0.67% P.*

R. I. 4437. Investigation of the Lander Phosphate Rock Deposits, Fremont County, Wyo. WILLIAM H. KING AND JOHN I. SCHUMACHER. Pp. 12; figs. 4; tbls. 2; drill holes. *Analysis of phosphatic rock section averaged 23.36% P_2O_5, 41.2% CaO, 13.7% SiO_2 and 2.55% F.*

Inf. Circ. 7495. Shaft-Sinking Methods and Costs and Cost of Plant and Equipment at the Fad Shaft, Eureka Corp., Ltd., Eureka, Nev. GEORGE W. MITCHELL AND A. C. JOHNSON. Pp. 17; figs. 15.

Inf. Circ. 7496. The Japanese Aluminum Industry. GLENN L. ALLEN AND VIRGIL MILLER. Pp. 56; figs. 22; tbls. 22. *Processes, rated annual capacity, and general information on each Japanese plant. Annual capacity of Japan for 1946 is estimated 115,700 metric tons, while the actual production in 1945 was 5,404 metric tons.*

Glossary of Clay Mineral Names. PAUL F. KERR AND P. K. HAMILTON. Pp. 68. Am. Petroleum Inst. Project 49, Clay Mineral Standards, Prel. Rept. 1, Columbia Univ., New York, February 1949. *Alphabetical list of minerals with history, origin, formula and short bibliography.*

Reference Clay Localities—United States. PAUL F. KERR AND J. L. KULP. Pp. 101; figs. 38; pls. 29. Am. Petroleum Inst. Project 49, Clay Mineral Standards, Prel. Rept. 2, Columbia Univ., New York, February, 1949. *A catalogue of localities of kaolin group, montmorillonite group, potash bentonite, hydromica or illite, attapulgite and pyrophyllite with brief descriptions of occurrences with sketches and photos.*

Oil and Gas Fields of Ohio. ROBERT L. ALKIRE, HAROLD J. FLINT, AND W. D. TURNBULL. Geol. Survey of Ohio, 1948. *Colored map, 39" x 51", scale 1" = 6 miles; generalized section of rocks and list of fields with producing sands.*

Petroleum Exploration in Eastern Arkansas with Selected Well Logs. CHARLES A. RENFROE. Pp. 159; figs. 2; pls. 3; tbls. 20. Arkansas Div. Geology, Bull 14, Little Rock, 1949. *Possibilities in Tertiary and Cretaceous rocks not good; Paleozoic production unknown.*

Geology and Ground-Water Resources of the Eastern Part of Colfax County, New Mexico. ROY L. GRIGGS. Pp. 187; pls. 8; figs. 10; tbls. 9. New Mexico Bur. Mines Ground-Water Rept. 1, Socorro, 1948.

Universidad de Tucumán—Jujuy, Argentina, 1948.

Pub. 455. Estudios Geológicos de Yacimientos Minerales de la Provincia de Jujuy. FEDERICO AHLFELD. Pp. 85; figs. 12; pls. 12. *Economic geology of the Jujuy gold deposits; general geology of the antimony and gold deposit of the Pabellón Mine, antimony deposits of Santa Catalina, iron and antimony deposits of Doncellas, lead-zinc deposits of Yavi, silver-lead deposits of "Pan de Azúcar," tin alluvium of the Cerro Negro ravine and tin deposits of Pululus highland.*

Pub. 457. Notas Preliminares sobre el Devónico de la parte Oriental de la Sierra de Zapla y del Cerro de Calilegua. JUAN J. P. DE BENEDETTI. Pp. 5; figs. 2. *Preliminary stratigraphic study in view of mapping the Province of Jujuy.*

Conselho Nacional do Petróleo—Brazil 1948.

Combustíveis Sintéticos. AVELINO IGNACIO DE OLIVEIRA. Pp. 13. *Description of processes to obtain synthetic fuels.*

Relatório de 1947. Pp. 216; figs. 27; numerous tables; colored geol. map, 40" x 28", scale, 1" = 2½ km. *Director's annual report containing administrative information, geology of each state and program for 1948.*

Department of Scientific and Industrial Research—New Zealand 1947-48.

The Outline of the Geology of New Zealand. BY OFFICERS OF THE GEOLOGICAL SURVEY. Pp. 47. *2 colored geol. maps, one 26" x 32" of the South Island, the other 25" x 34" of the North Island, scale, 1" = 16 miles.*

Bull. 42. The Geology of the Reefton Quartz Lodes. MAXWELL GAGE. Pp. 68; pls. 4; maps 16, some in color. *General geology, geological history, structure, structural relations of the lodes and history of quartz mining.*

Mem. 7. The Otaki Sandstone and its Geological History. R. L. OLIVER. Pp. 49; figs. 42; tbls. 3; 2 colored geol. maps, scale 1″ = 1 mi.

Metal Magic—The Story of the American Smelting and Refining Company. ISAAC F. MARCOSSON. Pp. 313; photos 33. Farrar, Straus and Company, Inc., New York, 1949. Price, $4.50. *A story of one of America's great mining and smelting companies and its world-wide operations. A colorful narrative and romance of a great mining company in its efforts, mostly successful, to develop and mine mineral resources in many parts of the world.*

Elements of Applied Hydrology. DON JOHNSTONE AND WILLIAM P. CROSS. Pp. 276; figs. 101; tbls. 32. Ronald Press Co., New York, 1949. Price, $5.00. *A text book for engineering students on the relations of rainfall, runoff, floods, infiltration and hydrology.*

Tin, its Mining, Production, Technology and Applications, 2nd Edit. C. L. MANTELL. Pp. 580; figs. 141; tbls. 58. American Chemical Society Monograph 51. Reinhold Publishing Corp., New York, 1949. Price, $10.00. *This new edition, more complete and larger, discusses mining, ore dressing, metallurgy, conservation, uses, and processes. Any one interested in tin must have it.*

Radioactive Measurements with Nuclear Emulsions. HERMAN YAGODA. Pp. 356; figs. 75; tbls. 31. John Wiley & Sons, Inc., New York, March 1949. Price, $5.00. *Detailed description of practical methods by which photographic emulsions are used to measure radioactivity; theory and practice; also biological and nuclear physics applications.*

SCIENTIFIC NOTES AND NEWS

HUGH D. MISER, of the U. S. Geological Survey, received the degree of Doctor of Laws from the University of Arkansas in June. The degree carried the citation: "your devotion to science and your high standards of scholarship and research have been a constant source of inspiration. You have explored many unknown paths of knowledge."

The Second Conference on Oil Shale and Cannel Coal, sponsored by the Institute of Petroleum, will meet in Glasgow, Scotland, during the week commencing July 3, 1950. The technical sessions shall be in three sections: Geology and Mining; Retorting, Refining, and Uses of By-products; Economics and Statistics. As 1950 is the centenary year of the James Young patent which led to the foundation of the Scottish shale oil industry, a Young Memorial Lecture will be celebrated at the same time.

The U. S. Geological Survey announces the publication of a report "The Geology and Ground-water Resources of the Pawtucket Quadrangle, R. I." which will enable industrialists, engineers, and farmers to locate additional water supplies and will lead to fuller utilization of this natural resource. Copies of the report may be obtained from the Rhode Island Port and Industrial Development Commission, 1405 Industrial Trust Building, Providence, R. I.

KARL T. COMPTON, Chairman of the Corporation of the Massachusetts Institute of Technology, has been elected to the Board of Directors of the McGraw-Hill Book Company.

DOUGLAS BALL, petroleum engineer, is now associated with Max W. Ball at 1025 Vermont Avenue, Washington 5, D. C.

ALBERTO J. TERRONES L., after a leave of absence in Mexico, has resumed his duties as geologist for the Cerro de Pasco Copper Corporation in Peru.

The American Academy of Arts and Sciences announces that income from its Permanent Science Fund will be disbursed as grants-in-aid in support of research projects in 19 fields, including geology, or any other science of any nature or description. Applications for grants-in-aid are receivable on multiple forms which will be supplied upon request to the chairman of the Permanent Science Fund Committee and are considered by the Committee on March 1 and October 1. Requests for further information about conditions governing the grants should be addressed to: Hudson Hoagland, Chairman, Permanent Science Fund Committee, Worcester Foundation for Experimental Biology, 222 Maple Avenue, Shrewsbury, Massachusetts.

The Economic Cooperation Administration has approved an industrial recovery project to increase the production of potash by Mines Demaniales de Potasses d'Alsace in the region northwest of Mulhouse, France. The project, by modernizing underground workings and providing new equipment for the potash mines, is expected to increase annual production from about 720,000 tons of pure potash in

1948 to 1,200,000 tons in 1957. The French reserves of potash are one of the principal sources of supply outside of Russia and the Russian zone of Germany.

Secretary of the Interior Julius A. Krug and Dr. Carey Croneis, president of Beloit College, Beloit, Wisconsin, will be the principal speakers on the opening day of the seventy-fifth anniversary of the Colorado School of Mines, September 29 and 30 and October 1, 1949. A general conference on the economics of the mineral industry will include "Economics of Gold Mining," by Donald H. McLaughlin, president of the Homestake Mining Company; "The Petroleum Policy of the United States," by Max Ball, petroleum consultant and former director of the oil and gas division of the United States Department of the Interior; "An Appraisal by the United States Geological Survey of the Mineral Resources of the United States," by S. J. Lasky of the United States Geological Survey. The program also includes separate conferences in the fields of coal mining, geophysics, metallurgy, metal mining, mining geology, petroleum geology and hydrology, engineering geology, petroleum production, petroleum refining, the industrial-minerals section of the American Institute of Mining and Metallurgical Engineers, and an excursion to the school's experimental mine at Idaho Springs.